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Implementation of a solar-biomass system for multi-family houses: Towards 100% renewable energy utilization

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ABSTRACT

The decarbonization of the building sector cannot preclude from the vast diffusion of renewable-sourced polygeneration systems for covering both heating and cooling demand. In this context, this study shows the potentialities of a system based on solar thermal collectors, a biomass boiler and an innovative reversible hybrid heat pump/ORC concept for addressing heating, cooling and domestic hot water demand of residential buildings. The potential is investigated in three cities (Madrid, Berlin and Helsinki), representative of the different European climates. The share of renewables in different seasons and building typologies is presented and the possibility of obtaining a 100% renewable system when the solution proposed is installed in new and renovated buildings is discussed. The results show that in standard multi-family houses, up to 70% of heating demand and 100% of cooling demand can be covered by the system in warmer climates and up to 60% share of renewables can be reached in Northern climates. Moreover, the flexible configuration of the system shows the potential for the application in the future energy system of the EU.

1. Introduction

The energy efficiency of buildings is a central topic in the agenda of international policy makers and governments. In the EU, where the building stocks accounts for 40% of overall energy consumption [1], a strong boost on energy efficiency measures for buildings is put into action by means of specific directives, such as the Energy Performance of Buildings Directive (EPBD [2]) and the Energy Efficiency Directive (EED [3]). Among the key points stated in the positioning papers and directives, there is the acknowledgements that most of the buildings that will make up the EU building stocks in 2050, are already existing. Therefore, the possibility of renovating and retrofitting them is essential. On the other hand, the EPBD introduces the specific requirements for all new buildings, and specifically all new buildings from December 31, 2020 must be nearly zero-energy buildings (nZEB). The effect of energy policies on the actual performance of buildings, was proven to be effective [4] and can lead up to 90% reduction of the energy consumption of a house when the best performing measures are applied [5].

In this framework, it is essential to work on different and integrated energy efficiency solutions, not only aimed at the optimization of energy efficiency during the construction of new buildings but considering their overall energy needs during their life-cycle span. The possible measures for enhancing the energy efficiency of buildings can be classified in three categories [1]:

- Passive measures: components and methods that affect thermal capacitance, transmittance and inertia, ambient and solar gains, and ventilation of buildings [6,7].
- Active measures: high-performance solutions for space heating/cooling and domestic hot water (DHW) production [8,9].
- Control techniques for building automation and management [10].

Considering active measures, there are two tendencies that allow reducing the primary energy needs of the energy system of a building: the use of advanced components in optimized configurations [8], and the integration of renewable energy sources that

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Nomenclature

A	area, m^2
a_0	zero-order coefficient solar collectors efficiency
a_1	first-order coefficient solar collectors efficiency, W/(m^2K)
a_2	second-order coefficient solar collectors efficiency, W/(m^2K^2)
G	Solar radiation, W/m^2
I	incident energy from solar collectors, kWh/m^2
$K_{\Phi l}$	Angle modifier in longitudinal direction
$K_{\Phi t}$	Angle modifier in transversal direction
Q	Energy, kJ
$\dot{Q}$	Thermal Power, kW
T	Temperature, °C
U	Heat transfer coefficient, W/(m^2 K)

Subscripts

amb	ambient
cond	condenser
evap	evaporator
m	medium
out	outlet

Abbreviations

COP	Coefficient of Performance
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
IAM	Incident Angle Modifier
HTF	Heat Transfer Fluid
HP	Heat Pump
NRB	New and Renovated Building
nZEB	Nearly-Zero Energy Building
PV-T	PhotoVoltaic Thermal
ORC	Organic Rankine Cycle
RES	Renewable Energy Source
SB	Standard Building
SF	Solar Fraction
TEG	ThermoElectric Generator
VCC	Vapour Compression Cycle

guarantees a step forward towards the reduction of CO_2 emissions and primary energy consumption [1]. Considering this latter approach, the best option to move towards a 100% self-consumption and 100% renewable scenario by 2050, is the use of a wide mix of energy sources [11] that are capable of generating not only heating/cooling but also electricity and DHW, thus covering the complete energy needs of a building.

Nowadays, most renewable-based solutions rely on a single power generation source, usually solar thermal or biomass for space heating and DHW, and PV or wind turbine for combined heating/cooling/DHW [9]. Great attention was given in the past years on fuel cell systems that can work as combined heat and power (CHP) systems for supplying heat and DHW to residential and non-residential buildings, mainly employing SOFC (Solid Oxide Fuel Cells) and PEMFC (Proton Exchange Membrane Fuel Cell) [12]. Fuel cell-powered systems, if coupled to heat pumps or thermal chillers (sorption chillers), can be used for provision of cooling during summer as demonstrated in Ref. [13]. However, the capacity ratio between thermal and electric energy of fuel cells can pose a problem in climates with high space heating demand, with the consequent need for a gas boiler back-up [14].

Another solution that is being investigated is the hybrid combination of wind and PV as dual-source energy systems [15,16] that can produce electricity to be used for direct use in buildings and to drive heat pumps. The findings in Ref. [15] show that the current market trends are towards a reduction of the cost for these technologies, that can be considered as valid alternatives to traditional power generators. However, there are some drawbacks in their application, mainly linked to the intermittency of the renewable sources, with a consequent need for storage systems (mainly batteries) and back-up generators.

Among the renewable energy sources for building applications, solar energy is widely applied worldwide, for direct heating and for direct production of DHW. An extensive literature is available on the subject [17]. The application of solar energy in hybrid systems mainly consists in the combination of solar thermal and solar photovoltaic (PV) systems for heating/cooling/DHW, with heat pumps and thermal energy storages. As reported in Ref. [18], the utilization of these hybrid systems, with a proper control, allows a high level of self-consumption and consistent energy savings. The co-generation of thermal and electric energy can also be obtained with photovoltaic-thermal (PV-T) panels. In Ref. [19], the analysis of a PV-T system for residential house is studied, showing that a COP of the heat pump up to 4.2 can be achieved. In order to achieve a high share of renewables, using solar energy as the only generation source, passive and active systems must be combined [20] and this is possible only in favourable climates and areas with low space heating demand and high solar irradiation. Another alternative hybrid solution that is gaining interest, is the combination of solar energy with Organic Rankine Cycles (ORC) for electricity and space heating demand. For instance, in Ref. [21] is presented a combined cooling, heating and power system that integrates parabolic through solar collectors with a single-effect absorption chiller and an ORC. The results indicate that a maximum solar efficiency of 94% for the combined production can be achieved, with up to 7% efficiency for power production. In Ref. [22], a hybrid system consisting of a PEMFC subsystem, an organic Rankine cycle/domestic hot water (ORC/DHW) subsystem and a vapour compression cycle (VCC) subsystem is presented. The flexibility of the system allows its operation also without sun or only as combined cooling and power production with an efficiency of 75% in winter and 85% in summer.

The literature survey presented shows that the majority of systems for residential or non-residential applications, present strong limitations in terms of application in different climates, overall share of renewables, or flexibility in supplying heating, cooling, DHW and electricity according to user needs. To overcome this gap, the EU-funded H2020 project SolBio-Rev is developing a flexible energy system for covering a large share of energy needs in buildings in a wide variety of climates. The system mainly relies on solar and biomass sources to cover heating and cooling demand of buildings and can be operated in different modes according to the location of installation and the season. In the present paper, the feasibility of the innovative solar-biomass driven system is explored, in a range of conditions able to cover almost all European cases. Compared to the solutions in this study, previous literature focused more on specific technologies, restricted geographical locations and emphasized on the specific technical parameters of the system analysed. Instead, in the present work, indications on the possible configurations and research directions in the perspective of a 100% renewable energy system in residential applications are given. The cases analysed demonstrate how it is possible to

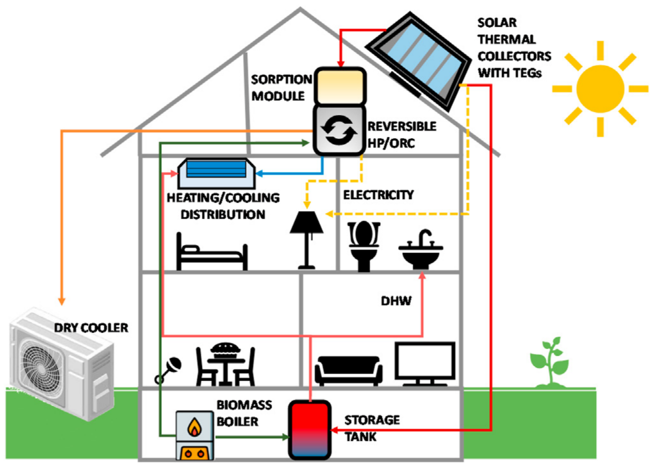

Fig. 1. General concept of SolBio-Rev hybrid system.

transition to a 100% renewable energy context in Europe. The suggested methodology is also framed in a way that makes it applicable to other cases globally.

The paper is structured as follows: in section 2, the system layout and operation in different climates and seasons are presented; in section 3, the methodology for the evaluation of the share of renewables in different cities and building typologies is described. Section 4 gives an overview of the energy demand of the buildings used for the study, whereas in sections 5 and 6 the results are presented and critically discussed.

2. SolBio-rev HYBRID SYSTEM

The overall concept of the hybrid system proposed is shown in Fig. 1. The main components of the system are: (1) solar thermal collectors with thermoelectric generators (TEGs) [23]; (2) a sorption module; (3) a reversible heat pump/ORC; and (4) a biomass boiler. The solar thermal collectors and biomass boiler represent the main heat sources for the system. When cooling is needed, the solar thermal collectors provide heat to the sorption module, which is connected in cascade with the heat pump, thus supplying space cooling with high efficiency to the user, according to the operating principle reported in Ref. [24,25] and clearly described in the following section. Space heating can be obtained directly by solar heat or, alternatively, by the biomass or through the heat pump. DHW is directly supplied by exploiting heat from the solar collectors or the biomass boiler. Electricity is produced by reversing the heat pump as ORC or by means of the TEGs connected to the solar collectors. The heat to the ORC can be supplied by either solar collectors or biomass boiler. The condensation and adsorption heat from the sorption module and heat pump is released to the ambient by means of a dry cooler. The actual configuration of the system includes some additional heat exchangers for separating the different circuits. For instance, the dry cooler circuit is equipped with a plate heat exchanger that separates the water/glycol mixture needed for winter operation from the water in the distribution circuit. Similarly, the storage tank includes a heat exchanger for DHW (as prescribed by regulations) and the connection of the biomass boiler to the ORC is done through a dedicated heat exchanger, to allow working with pressurised water at 4 bar to increase the operating temperature and therefore the efficiency of the ORC.

The main features of the hybrid system proposed include the exploitation of solar heat in a wide temperature range, from 15 °C to 95 °C and an innovative heat pump configuration. This consists of two main components, the sorption module and the reversible heat pump, connected in cascade. Indeed, the cascade configurations of such components allows an increase in the efficiency of the reversible heat pump for cooling production up to 40% [24,25]. The reversible HP/ORC is instead based on the capability of reversible operation of the components used in conventional heat pumps and, in particular, the volumetric compressor. Such a concept was already explored for industrial recovery of low-grade heat and for power-to-heat applications for storing excess heat from renewables [26,27] and was proved to be feasible. The more general reversible heat pump/ORC concept is shown in Fig. 2: during heat pump operation (Fig. 2b), the compressor is operated and heating is provided at the condenser (in winter), whereas cooling is provided at the evaporator (in summer). At ORC mode (Fig. 2c), solar or biomass heat supplies the evaporator for power production by the expander. Heat rejected at the condenser can be used for space heating when needed or rejected to the ambient.

Moreover, in the present case, the heat pump is further integrated with the sorption module, so that in summer the chilled water produced by the sorption module is used to cool down the condenser of the heat pump. During winter, instead, the sorption module is not working and the heat pump is directly connected either to the dry cooler or the storage tank, which supply ambient or solar heat as evaporation source respectively, and to the user circuit for provision of space heating. The operation of the combined heat pump-sorption module is shown in Fig. 3.

The integration of TEGs with solar collectors has also been recently studied in the literature [28,29]. For the present case, it was considered that the TEG block is installed in the HTF circuit of the solar collectors, so that, according to controls and temperature levels, when TEGs are operated, the solar fluid passes through them and allows their operation for electricity production. This leads to a compact system that can utilize heat at a broad temperature range, in order to meet the buildings energy needs. To better understand the operation of the system, the main operating modes during the different seasons are shown in Fig. 4.

During summer:

- DHW is provided by solar collectors, connected to the storage tank.
- Space cooling is provided by the sorption module and the reversible heat pump. In warm climates, the sorption module takes heat at 80–90 °C from the solar thermal collectors and produces chilled water at 16–20 °C. The sorption module is working in cascade with the reversible heat pump and it is used to cool down the condenser of the reversible heat pump. Space cooling is provided to the user in the temperature range of 5–15 °C from the evaporator of the heat pump. In order to have a peak shaving effect both during summer and winter, a small thermal buffer is connected to the reversible heat pump and the user distribution system to store the energy produced by this component. In cold climates, the sorption module is not installed and therefore cooling is provided by the reversible heat pump (this is also the case for warm climates when there is no sun). Both in warm and cold climates, the heat rejected is dissipated in the ambient by means of the dry cooler.
- Electricity is mainly provided by the grid. However, when there is no need for space cooling, this can be provided by the ORC, that uses the heat from solar collectors as the heat source (when heat at temperatures higher than 90 °C is available), or by the TEGs (when there is the heat at a temperature level of 60–70 °C).

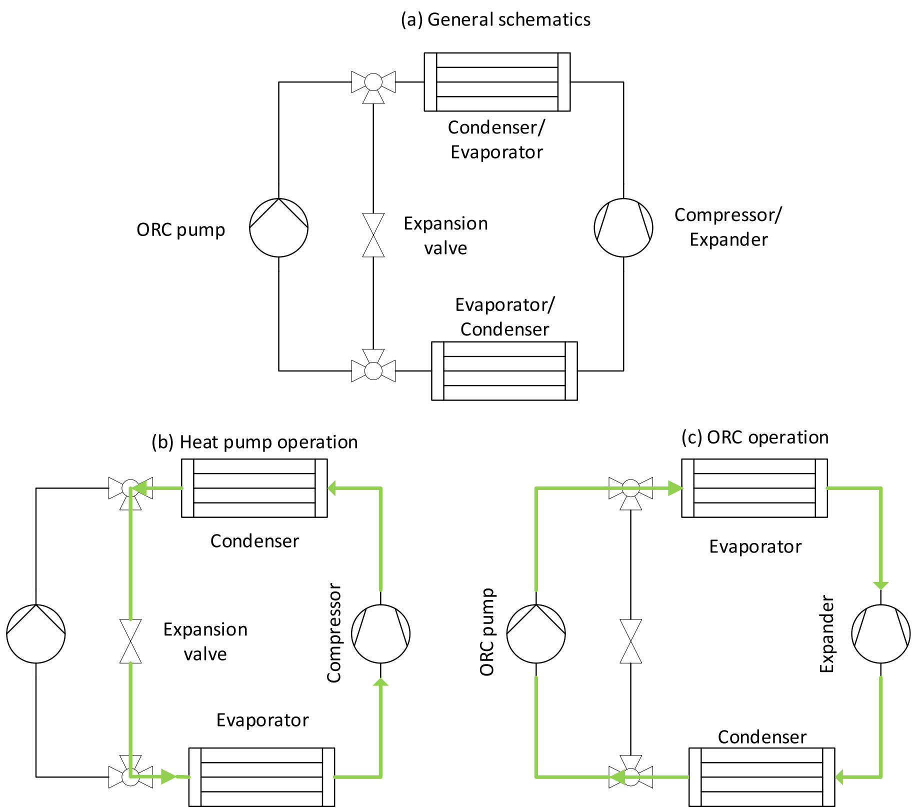

Fig. 2. Schematics of reversible heat pump/ORC. (a) general layout of the concept; (b) operation as heat pump; (c) operation as ORC.

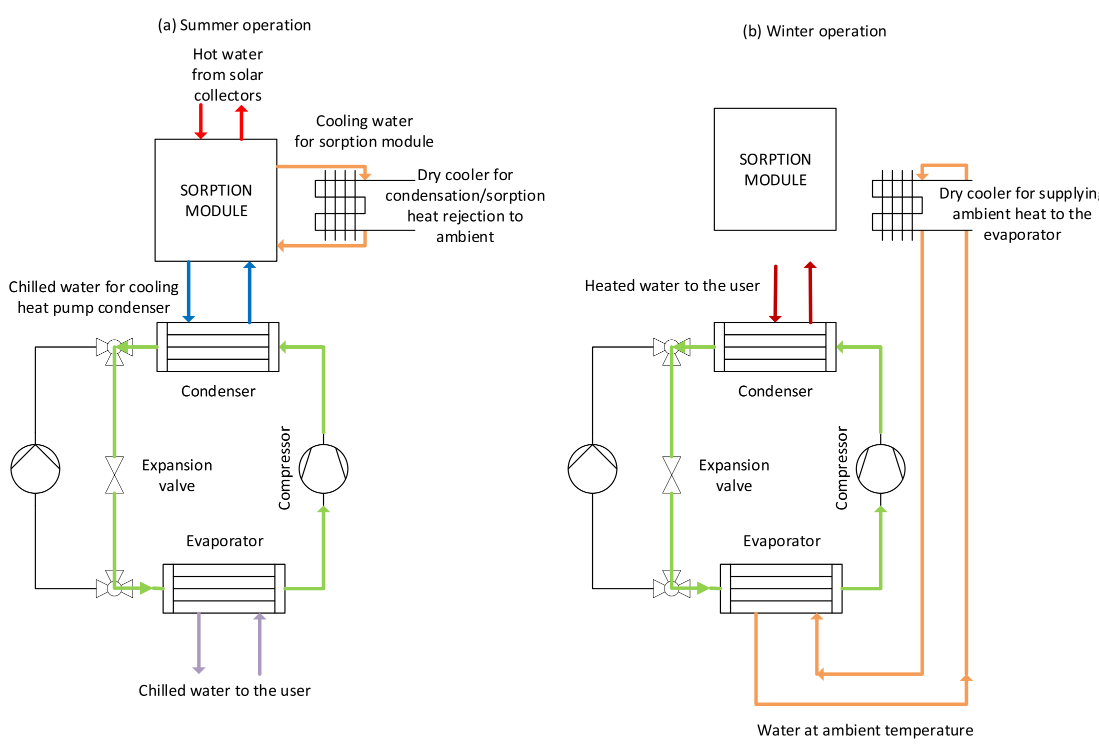

Fig. 3. Integration of the heat pump with the sorption module. (a) Summer operation; (b) winter operation.

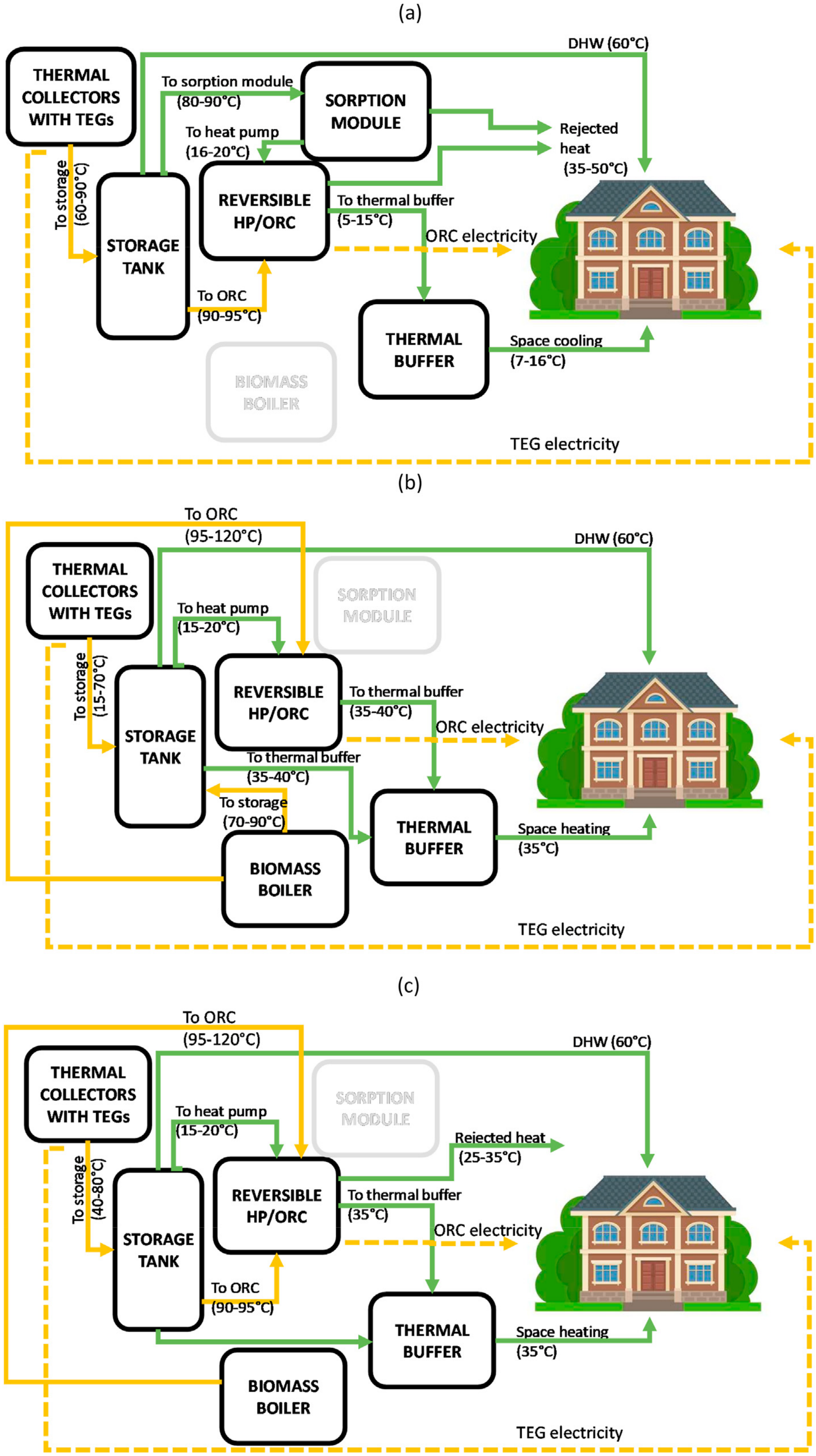

Fig. 4. Main operating modes of the hybrid system in (a) summer; (b) winter; (c) intermediate seasons.

During winter:

- DHW is provided by either the solar collectors or the biomass boiler, if solar heat is not at a sufficient temperature level.
- Space heating can be provided by: (1) solar collectors if there is heat at least 35 °C (or if there is heat at higher temperatures available but there is no need for DHW); (2) the reversible heat pump working in solar-assisted mode, i.e. exploiting heat at low temperature (15–20 °C) from solar collectors as heat source for evaporation; (3) the biomass boiler.
- Electricity is mainly provided by the grid. However, if biomass boiler power exceeds the thermal power needed from the ORC and the space heating demand this can be provided by the ORC, that uses the heat from biomass boiler, or by the TEGs (when there is solar heat at a temperature level of 50–60 °C).

During intermediate seasons:

- DHW is provided by solar thermal collectors, using biomass boiler as back-up if needed.
- Space heating (if needed) is provided by solar thermal collectors or by the reversible heat pump exploiting either solar or ambient heat as heat source for evaporation.
- Electricity is mainly provided by TEGs or the ORC. The latter one uses biomass boiler as the main heat source, but the solar-driven operation is possible in warm countries.

The system described is certainly characterised by a high number of components in its most general configuration. As will be discussed in section 6.1, for different building types and different locations, it is possible to keep the efficiency of the system high, while reducing the number of components needed. The main advantage of the proposed hybrid system, e.g. over the hybrid PV-T with heat pump solution, is the higher adaptability to different climates, loads and seasons whereas the PV-T/heat pump solution is mostly suitable for addressing only heating needs and, furthermore, a back-up system is needed for DHW [30]. In addition, the share of renewables that can be achieved with the PV-T with heat pump is usually lower than 60%, whereas the aim of the present system is to go towards a 100% renewables scenario [30,31]. In comparison with ground-source heat pumps system, constraints related to the drilling for boreholes heat exchanger are eliminated [32], still having the possibility of using low-temperature heat as heat source for evaporation during winter. The numerous and variable operating modes described allow for a high degree of flexibility of the system, making it suitable for buildings with different energy needs and situated in different climates. Therefore, the analysis on the potentialities of hybrid system cannot preclude from the specificities of the installation (i.e. the location and type of building). The first step in the evaluation was then focused on the analysis of the building stocks in different countries, representative of European climate zones, and in different building types, that are presented in the next section.

3. Methodology

The methodology followed in this step of the analysis is schematically presented in Fig. 5.

The first step of the study was a comprehensive evaluation of the building stock in Europe, with the aim of defining the heating, cooling and domestic hot water demand that the hybrid SolBio-Rev system should cover. To this aim, a review of the literature available and open access databases that include the characterization of different building typologies was carried out.

The building typology that was considered the most suitable for the SolBio-Rev system are multi-family houses. For a better evaluation of the system potentiality, however, two cases were selected: standard building (i.e. as built, without renovation, SBs) and new and renovated buildings (NRBs). The heating, cooling and DHW demands for SBs refer to the ones reported in the project ENTRANZE [33]. In this database the energy needs are evaluated through simulations on a reference building. In the case of SBs the reference building is a south/north-oriented four-floor building that includes 12–16 dwellings with a conditioned area around 1000 m^2. The monthly energy demand was calculated considering an indoor set point of 21 °C with a 30% of humidity in winter, and 26 °C and with a 70% of humidity in summer with a ventilation rate was considered to be 0.8 air changes/hour. The DHW demand is calculated by applying the Standard EN 15316-3-1. The information regarding the NRBs are based on the information available from Concerted Action on Energy Performance of Buildings (CA EPBD) [34] and a survey of the literature. More details on building characteristics and energy demand are reported in section 4. The data for the building energy demand and the weather data are taken, respectively, from ENTRANZE project and Meteonorm data. In both cases, the data sets are in the form of a year of hourly data synthesized to represent long-term statistical trends and patterns.

The reason for choosing multi-family houses instead of other building typologies (i.e. single-family houses) is due to the intrinsic complexity of the system and the difficulty in sizing some of the

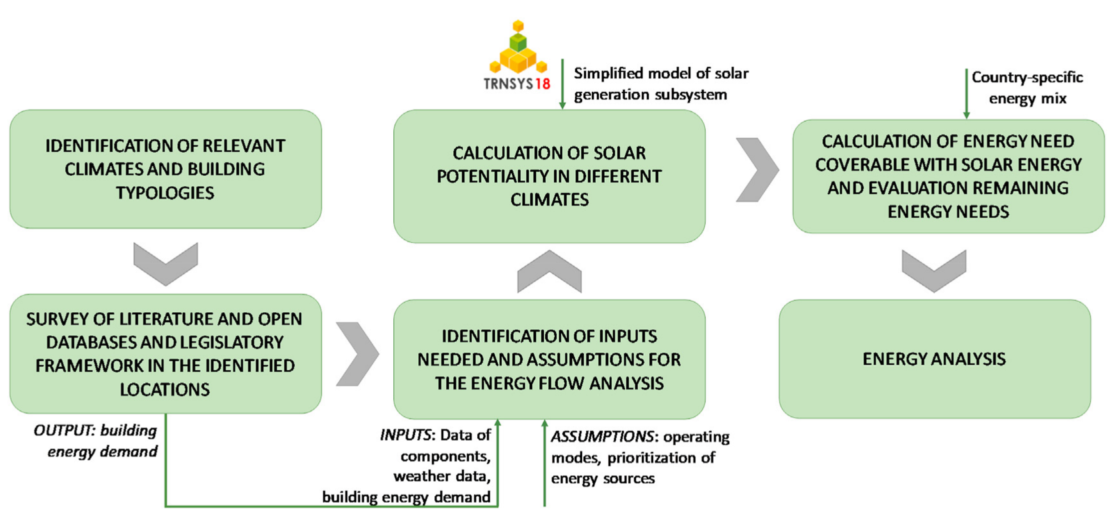

Fig. 5. Methodology followed in the analysis including the evaluation of relevant building energy demand and the steps needed for the energy analysis.

components (such as the heat pump and the sorption module) for the lower loads associated to single-family buildings, since commercial components are usually in bigger sizes. On the contrary, results could be scaled and remain meaningful for e.g. offices and school buildings, where heating and cooling demand are relevant compared to DHW and the volume of the building justifies the number of components needed in the system.

The results were used as input for the systematic assessment of the hybrid system in different climates. Hence, a TRNSYS model was realised to identify the solar potentiality in different climates. Input data are weather conditions of the location chosen, the performance data of solar collectors and the main operating modes for the system in different seasons. Subsequently, considering the energy demand of buildings, the amount of energy that can be covered by solar was calculated. Finally, based on the energy mix and the climate conditions, an estimation on the best alternative to cover demand from other sources (biomass, reversible heat pump) was considered and the overall energy flows were used to evaluate the shares of renewables achievable in different scenarios.

One of the peculiarities of the hybrid solar-biomass system is the flexibility and the possibility to operate in several combinations. For the analysis here presented, the following assumptions were made:

1. The hydraulic circuit of the solar collectors is equipped with a variable speed pump and its speed is varied according to the desired outlet temperature. This, in turn, depends on the daily weather conditions and the user needs.
2. Regarding the provision of DHW, the priority is given to solar heat, followed by the biomass boiler.
3. Regarding heating demand, the highest priority is given to solar heat. All the heat at 35 °C is used for space heating, but also part of the heat at higher temperatures can be used for this purpose, if there is no need for DHW. The second sub-system, by order of priority, for the provision of space heating is the heat pump, that is operated with solar heat at 15 °C as heat source for evaporation, in order to increase its efficiency. The remaining demand is covered by the biomass boiler.
4. Regarding space cooling provision, in warm climates the cascade combination of sorption module and reversible heat pump is used; in colder climates the reversible heat pump covers the whole cooling demand.
5. The ORC and TEGs are operated only when there is no heat demand from the other components and the electricity produced is used only for driving the reversible heat pump and the auxiliaries of the system. This means that in warm climates, since the heat at 90 °C in summer is used for driving the sorption unit in the cascade, the ORC can be used mainly in intermediate seasons when the reversible heat pump is not providing any space heating/cooling. In this case, the TEGs are the prioritised system for electricity generation. The demand that cannot be met by solar conversion, is taken from the national grid. In colder climates, the heat at 90 °C during summer that is not used by other components can be used to drive the ORC. It is worth noticing that, in real system operations, the ORC can be also driven by the biomass or by the combination of solar and biomass. However, in the present analysis, this solution was not considered because the electricity demand, which is strictly related to occupancy profile and user behaviour, is not known and, therefore, it is difficult to estimate the hours of operation needed.
6. The efficiency of solar collectors depends on ambient temperature and solar collectors' temperature, whereas the efficiency of the cascade sorption module, ORC and TEGs is considered to be constant. For the sorption module, a thermal efficiency (COP) of 0.5 was assumed [24,35]; for ORC an efficiency of 4% was assumed [36], while for TEGs an efficiency of 2.5% was used as reference value [37]. Additionally, the performance of the reversible heat pump for space heating supply was assumed to be constant, with a COP equal to 3.3 for solar-assisted operation. For the compression unit working in summer mode, the EER (Energy Efficiency Ratio, i.e. the ratio of cooling output/electric input) considered is 4 for combined operation with the adsorption module and 2.5 for operation as a stand-alone unit. Such efficiencies are considered constant regardless of ambient conditions or part load behaviour. Even though this is a simplifying assumption, it serves the scope of the paper, i.e. giving information on the theoretical achievable performance of the system rather than detailed dynamic performance. To this aim, the performance figures used were chosen using a cautionary approach and therefore are in the low-medium range of the ones theoretically achievable for the components that are under development in the current research activities. For instance, regarding ORC, the assumption of constant efficiency reflects the different operating conditions during the year. In this way, in winter or summer operation, ORC is expected to be cooled by the heating loop of the building or the hot ambient respectively, leading to higher condensation temperatures (40–50 °C), whereas in intermediate season operation, ambient heat of lower temperature is used as cooling medium resulting in lower condensation temperature and pressure. This fact in conjunction with the varying temperature and flow rate of the heat source at the evaporator leads to different pressure ratios in the cycle and thus, to different efficiencies which are expected to range around 4%.
7. The storage tank is able to keep the desired temperature level for covering daily DHW or DHW/heating demand. The sizing procedure for the storage tank in order to comply with this criterion is described in Appendix C.

4. Energy demand of buildings in different climates

Starting point of the analysis is the evaluation of the boundary conditions, i.e. the energy demand of different building typologies in different EU climate zones. The hybrid system proposed can be suitable in buildings with a high demand of heating and cooling energy in both residential and commercial sector. In this context, multi-family houses are considered, belonging to different construction typologies of standard buildings (SBs) and new and Renovated Buildings (NRBs).

In particular, the choice of NRBs is strongly motivated by the Energy Performance of Buildings Directive (EPBD) that is bringing Europe towards a high efficiency buildings scenario. The current EU regulations (Directive 2010/31/EU) requires all the new buildings to be nearly-zero energy buildings (nZEBs) by the end of 2020. An nZEB can be defined as a building with high energy performance, where the minimum requirements and the standard guidelines to evaluate the energy performance are defined for each EU country, in national plans based on the EPBD. The main characteristics and the energy requirements of the building typologies selected, strictly depend on the location of the building. Therefore, the feasibility of the hybrid system proposed was evaluated considering the energy demand of the building categories selected in three locations corresponding to the North, Central and South Europe climates, namely, Madrid, Berlin, and Helsinki.

4.1. Characteristics and energy demand of standard buildings in Madrid, Berlin and Helsinki

The data regarding the building construction characteristics and

Table 1
Average U-values for SBs considering multi-family houses in Spain, Germany and Finland [33].

Country	U-value [W/m²K]			
	Walls	Roof	Basement	Windows
Spain	1.46	1.92	1.30	5.70
Germany	1.44	1.17	1.50	2.11
Finland	0.60	0.39	0.47	2.79

the energy demand used in the present study are obtained from open access databases such as TABULA/EPISCOPE [38] and ENTRANZE. Table 1 reports the U-values used in the project ENTRANZE [33] to calculate the energy demand for heating and cooling of multi-family houses in the three selected locations.

Fig. 6 shows the value of the energy demand (heating, cooling and DHW) of the SBs considering multi-family houses located in Madrid, Berlin and Helsinki as taken from the ENTRANZE database [33]. In Madrid (Fig. 6a), the months with the highest heating demand are January and December (16 kWh/m^2). During summer, cooling is needed from June until September with highest cooling demand in July (10 kWh/m^2). In Berlin and Helsinki (Figs. 6b and 4c), heating is needed throughout the year. After the summer months, the heating demand rapidly increases from September, reaching a maximum in January and December (around 25 kWh/m^2 for both locations). In Berlin, cooling demand is required in the summer months, with the highest demand in July (3 kWh/m^2), while in Helsinki cooling is only required in August (around 0.5 kWh/m^2). In all the locations selected the demand of DHW can be considered constant during the year (between 1 kWh/m^2 and 2 kWh/m^2).

4.2. New and renovated buildings requirements in Spain, Germany and Finland

As will be detailed in the following sections, the potentiality of the SolBio-Rev hybrid system cannot preclude from the evaluation of its installation in recent (or recently renovated) buildings. To this aim, the energy requirements in the three climates selected were analysed, on the basis of law requirements and existing data.

The building regulation in Spain that defines the basic requirements is the “Ley de Ordenación de la Edificación de España”. The document that regulates the energy efficiency in buildings is the Royal Decree 235/2013 (Documento Basico de Ahorro de Energia—DBHE) and includes the obligation for all the new energy buildings to be nZEB after 2020 (after 2018 for public buildings) [39]. The energy performance requirements for new and existing buildings are contained in the Technical Building Code (CTE) [40]. The main indicators used as a basis of an nZEB in Spain are primary energy use, energy demand for heating and cooling, and the building CO_2 emissions. Since the building performance is related to their location, the “Documento descriptivo climas de referencia” divides the country in six different climate zones and four summer climate zones. In Germany, the energy performance requirements are defined by the Energy Saving Ordinance (EnEV). The efficiency of new residential buildings is determined with a comparison with a reference building that can be done with two different calculation methods (DIN V 4108-6 combined with DIN V 4701-10, or the DIN V 18599) [41]. For the existing residential buildings, conditional requirements are mandatory in the case of a major renovation. For non-residential buildings, DIN V 18599 is a mandatory calculation method to define energy performance. In Finland, the energy efficiency in buildings is regulated by the National Building code that defines the requirements of the building energy consumption that

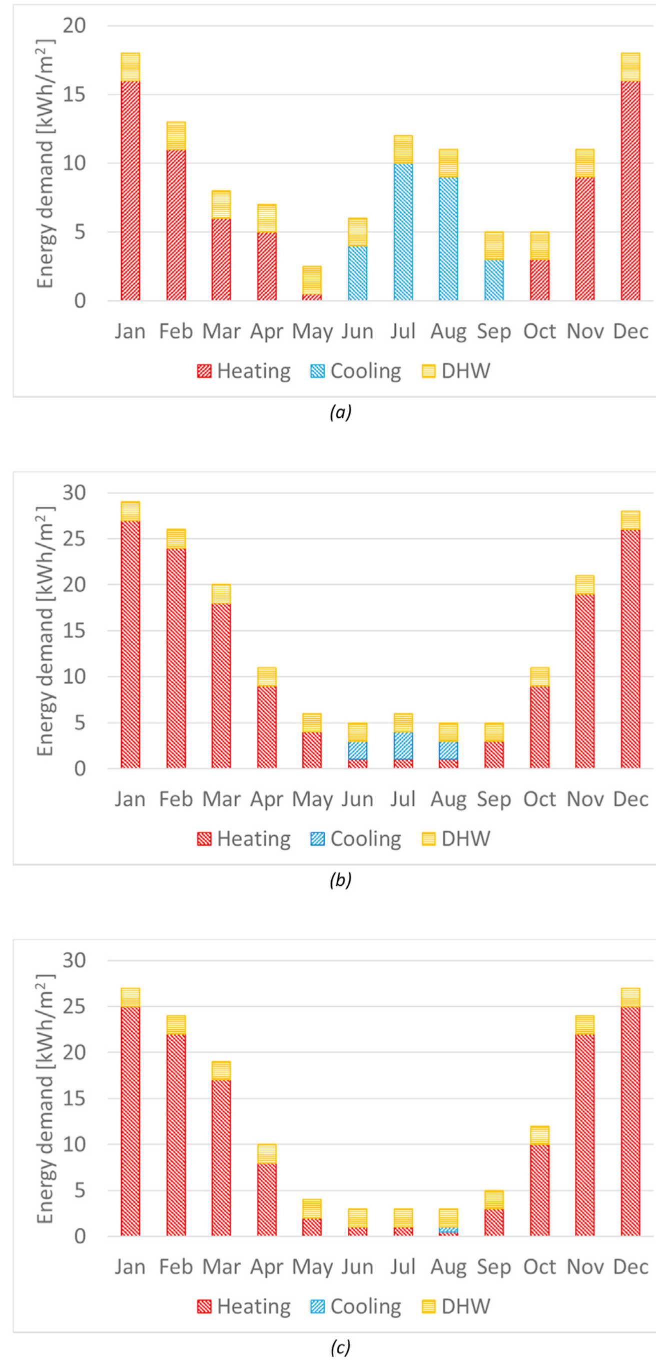

Fig. 6. Monthly energy needs for heating, cooling and DHW of SBs considering multi-family houses located in Madrid (a), Berlin (b) and Helsinki (c) [33].

is calculated taking into account the energy source, setting a maximum value of the overall energy consumption, depending on the building typology.

In the new building stock in Finland, the maximum overall energy consumption is calculated considering the primary energy factor that is lower for renewable energy sources and sources of district heating/cooling. Table 2 reports the U-value requirements for new buildings and the primary energy consumption for NRBs.

In the present analysis, the energy demand of the NRBs in Spain was calculated as 45% of SBs considering that energy consumption of SBs is 120 kWh/(m^2 year) and the regulation for NRBs allows for maximum 45 kWh/(m^2 year). A correction factor was used to take

Table 2
U-value requirements and primary energy consumption for NRBs in Spain, Germany and Finland.

Country	U-value [W/m^2·K]					Primary energy consumption [kWh/m^2 year]
	Walls	Roof	Floor	Windows	Doors	–
Spain [40]	0.23–0.56	0.19–0.50	0.48–0.80	1.5–2.7	–	40/86
Germany [41,42]	0.28	0.20	0.35	1.3	1.8	65/100
Finland [41]	0.17	0.09	0.09	1	1	90

into account the larger area of the new buildings typically realised. Using the same approach, in Germany the energy demand of the NRBs was considered to be 90% of the one of SBs from the existing building stock. In Finland, the energy demand of NRBs was calculated as 80% of the one of SBs, which is 160 kWh/(m^2 year) considering the energy constraints from regulations on the maximum annual consumption.

4.3. Characteristics of the buildings selected

Starting from the analysis of the building stocks, the typical size of the buildings in different climates was evaluated and used for the subsequent analysis. Rooftop and conditioned area in the various locations are reported in Table 3. For both SBs and NRBs, the same rooftop and conditioned area were considered.

All the analyses are done considering two different sizes of the solar collectors' field, namely 50% of overall rooftop area covered by solar collectors and 100% of rooftop area covered by solar collectors. Such a value refers to the area needed for the installation of solar collectors. To calculate the effective solar collectors area it is necessary to take into account the inclination of the collectors and the distance to avoid shading [43]. The actual available area for solar collectors in the two examined cases is shown in Table 3. It is worth stating that all the results presented in the next section were normalised per unit area of the building, for fair comparison. Nonetheless, the characteristics of the national building stock in the countries were taken into account by the different shape factor of the buildings, which corresponds to a different useful area for solar collectors in the various cases.

5. Systematic assessment of the hybrid system

A summary of all simulations and main assumptions used is given in Table 4. In the following sections, results are presented and discussed.

5.1. Calculation of solar heat available

The solar potentiality of the hybrid system is intended as the amount of solar heat available in different climates and in the different seasons. To this aim, a model was realised in TRNSYS18 environment, whose schematic layout is reported in Fig. 7: the solar collectors, modelled by means of type 539, are connected through lumped nodes representing the hydraulic circuit of the solar field (type 31) to a thermal dissipator, that keeps the ΔT between inlet and outlet of the heat transfer fluid (HTF) of the solar collectors at a certain value; for the current simulations $\Delta T_{set} = 10$ K was chosen. Type 539 already includes a variable speed pump that regulates the flow rate according to different control strategies. In the present case, the management chosen is the one that allows keeping a

Table 3
Average conditioned area and rooftop surface for the examined countries.

Country	Rooftop [m^2]	Conditioned area [m^2]	Useful solar collectors' area for 50% rooftop overall space occupied [m^2]	Useful solar collectors' area for 100% rooftop overall space occupied [m^2]
Finland	400	1000	120	240
Germany	200	800	70	140
Spain	100	400	75	150

Table 4
Summary of simulations and main assumptions.

	Useful solar collectors' area [m^2]	Sorption module	ORC	Heat pump- winter mode	Heat pump- summer mode	TEGs
Madrid, SBs-50%	75	COP = 0.5	η_{el} = 4%	EER = 3.3	EER = 4 (cascade operation), EER = 2.5 stand-alone operation	η_{el} = 2.5%
Madrid, SBs-100%	150	COP = 0.5	η_{el} = 4%	EER = 3.3	EER = 4 (cascade operation), EER = 2.5 stand-alone operation	η_{el} = 2.5%
Madrid, NRBs-50%	75	COP = 0.5	η_{el} = 4%	EER = 3.3	EER = 4 (cascade operation), EER = 2.5 stand-alone operation	η_{el} = 2.5%
Madrid, NRBs-100%	150	COP = 0.5	η_{el} = 4%	EER = 3.3	EER = 4 (cascade operation), EER = 2.5 stand-alone operation	η_{el} = 2.5%
Berlin, SBs-50%	70	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Berlin, SBs-100%	140	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Berlin, NRBs-50%	70	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Berlin, NRBs-100%	140	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Helsinki, SBs-50%	120	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Helsinki, SBs-100%	240	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Helsinki, NRBs-50%	120	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%
Helsinki, NRBs-100%	240	not installed	η_{el} = 4%	EER = 3.3	EER = 2.5	η_{el} = 2.5%

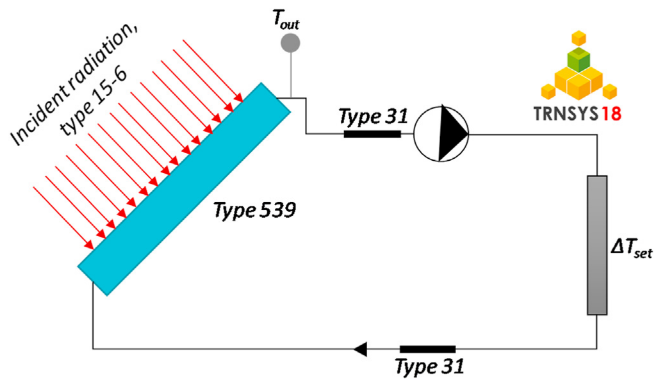

Fig. 7. Schematic layout of TRNSYS model realised.

defined outlet temperature at the outlet of the solar collectors T_{out}. The data of the solar collectors and the main parameters used in the TRNSYS model, as well as a more detailed explanation of the types used, are given in Appendix A.

The desired outlet temperature T_{out} is controlled dynamically according to different criteria, i.e. solar irradiation, ambient temperature and DHW demand:

- When solar irradiation is higher than 500 W/m^2, T_{out} = 60 °C for DHW production up to 0.05 kWh/m^2/d. Otherwise, T_{out} = 90 °C in summer for driving the sorption chiller and T_{out} = 80 °C in other months to drive the ORC, which is the threshold temperature for solar-assisted ORC operation.
- When solar irradiation is between 500 W/m^2 and 300 W/m^2, T_{out} = 60 °C for DHW production up to 0.05 kWh/m^2/d. Otherwise, if the average ambient temperature for the day is equal or lower than 15 °C, T_{out} = 35 °C for space heating. If there is no DHW need and the temperature of the day is higher than 15 °C, the heat is not used.
- When solar irradiation is lower than 300 W/m^2, if average ambient temperature for the day is lower than 15 °C, T_{out} = 15 °C to use the solar heat as heat source for the reversible HP/ORC, otherwise heat is not used.

Such a control is schematically shown in Fig. 8.

The results are shown in Fig. 9, where the solar heat available at the different temperature levels is reported for the cities studied. In Madrid, heat at 80–90 °C is available from March till October from 60 kWh/m^2 in October up to 100 kWh/m^2 in August. During winter, there is still a significant amount of heat at 60 °C, which is useful for DHW, i.e. around 35 kWh/m^2 in January and February and 30 kWh/m^2 in November and December. In Berlin, heat at 80–90 °C is available from April till October from 30 kWh/m^2 in April and September up to 50 kWh/m^2 in August. During winter, heat at 60 °C is available mainly in February, March and November, with a maximum of 18 kWh/m^2 in March. In Helsinki, heat at 80–90 °C is available in March.

In the Figures, also the overall incident energy per unit area is displayed, which is calculated as:

$$I = \int_{t=1\ h}^{t=8760\ h} G(t)\, dt \tag{1}$$

5.2. Solar fraction in different climates

The main goal of the hybrid system here presented is to maximise the share of renewables in covering the energy demand of the building (for heating/cooling, DHW and electricity). To reach such a goal, a specific prioritisation of the generators for different climates and seasons was considered, which is based on the assumptions reported in section 3. The electricity produced is used for the operation of the reversible heat pump and the auxiliaries of the system. The equations used to calculate the different energy contributions are reported in Appendix B.

Starting from the energy demand and for the various buildings and the solar heat available from the collectors, the solar fraction for each case can be calculated as follows:

$$SF_{DHW} = \frac{DHW_{met}}{DHW_{demand}} \tag{2}$$

$$SF_{heating} = \frac{heating_{met}}{heating_{demand}} \tag{3}$$

where the subscript "met" indicates the amount of DHW or heating demand that is directly supplied by solar thermal collectors, whereas the subscript "demand" indicates the overall annual demand for DHW or space heating of the building under investigation.

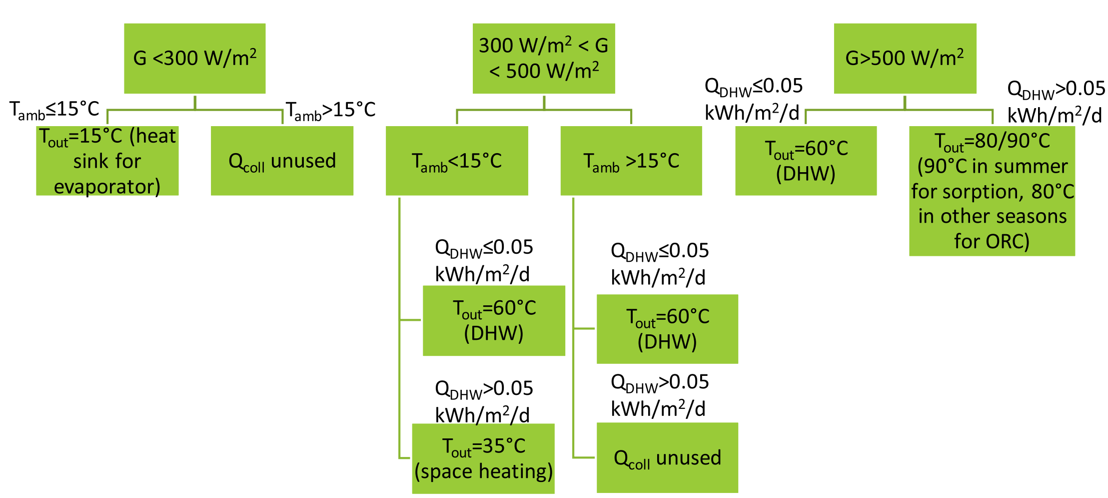

Fig. 8. Control of the outlet temperature from solar collector according to operating conditions.

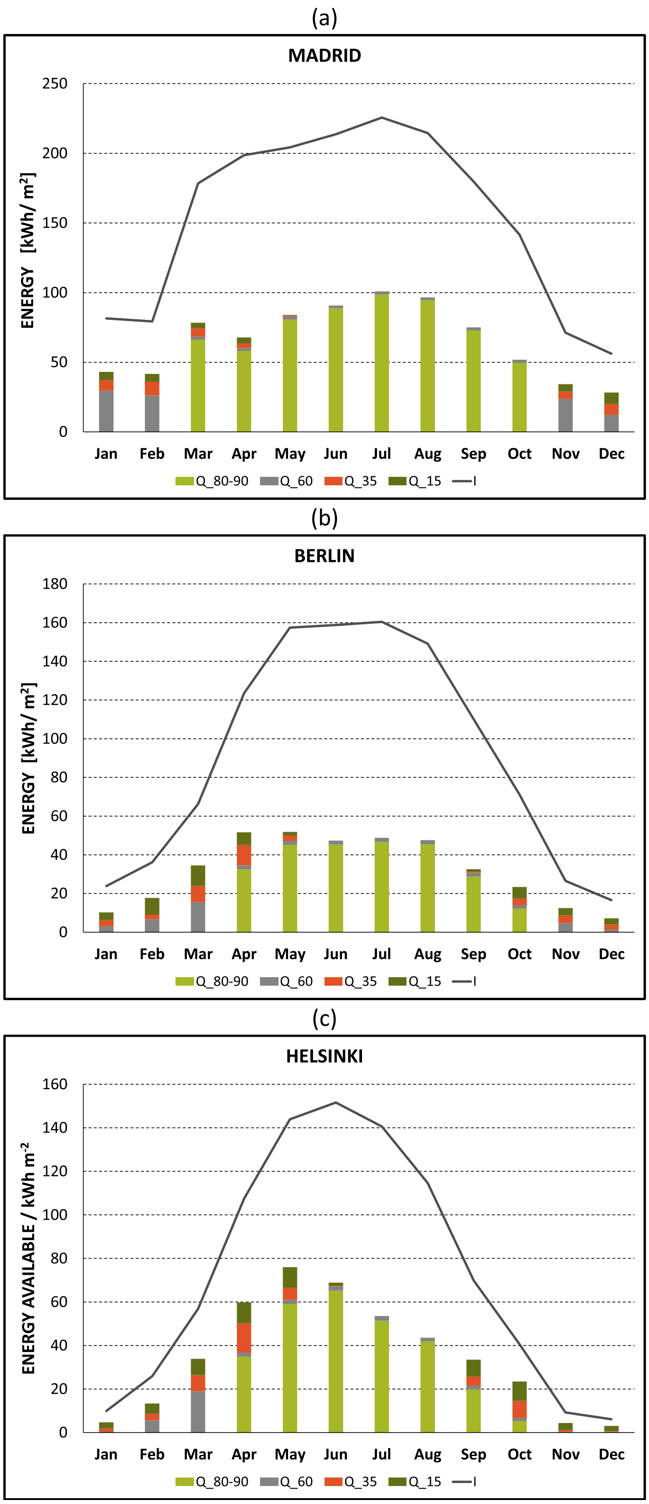

Fig. 9. Solar heat available at different temperature levels in (a) Madrid, (b) Berlin and (c) Helsinki.

The $SF_{heating}$ takes into account only the direct space heating with solar, without considering the use of solar heat as evaporator source of the heat pump.

The results are shown in Fig. 10 on monthly basis. It is possible to notice that in Madrid (Fig. 10a) $SF_{heating}$ higher than 50% can be achieved when 100% of rooftop is covered with solar collectors, in NRBs in January, February and December and between 30% and 40% for NRBs in March and for SBs in the whole winter season. The advantage of better insulation of NRBs over SBs is then more evident in colder seasons, when the heat from solar collectors can be exploited to a greater extent in NRBs (i.e. up to 50% against 30% of SBs from November to February). In Berlin (Fig. 10c), the $SF_{heating}$ is especially high in intermediate seasons, due to the lower energy demand and the higher solar radiation. Indeed, from March to May it is possible to get from 30% to 40% of overall heating load directly from solar, whereas during winter only about 10% of the load is supplied by solar collectors. The difference between SBs and NRBs is not marked since, as already pointed out in sections 4.1 and 4.2 the difference in the construction of the buildings (from U-values point of view) is not marked. In Helsinki (Fig. 10e), the situation is similar to Berlin: during spring, 30–40% of heating demand is supplied by the solar heating system, a fraction that drops to about 20% in autumn and below 10% in winter. Due to the good insulation of the buildings (even for the SBs), the difference between the SBs and NRBs is less than 10%. It can be also noticed that, contrarily to the case of Madrid, the difference between the two extensions of solar collectors is not high since it is penalized by the very low solar irradiation at the high latitude.

Looking at SF_{DHW}, the values for all the different cases are quite high. In this case, the difference between the two rooftop coverages (50% and 100%), both for SBs and NRBs is more clearly marked for colder climates. Indeed, in Madrid (Fig. 10b), it is possible to cover the whole DHW demand already with 50% of rooftop, thanks to the higher solar radiation. During summer, SF_{DHW} is instead low, which represents a counterintuitive result and it is linked to the priorities given: in summer, the vast majority of heat is exploited to run the cascade chiller for covering cooling demand with high efficiency. However, a proper control strategy could be applied to ensure that solar radiation can supply the whole DHW even during these months. In Berlin (Fig. 10d), during intermediate seasons (February to May and September to November) the SF_{DHW} is 100% as well, even with 50% rooftop area. Even in this case, during summer the solar fraction is lower: this is due to the fact that the heat at higher temperatures is used to drive the TEGs to produce the electricity to feed the heat pump, but, also in this case, a proper control strategy could be applied to ensure $SF_{DHW} = 100\%$ even in summer. The situation is different in Helsinki (Fig. 10f), where during winter less than 10% of DHW can be produced by exploiting solar heat, whereas in intermediate seasons and in summer it is possible to reach 100% of SF_{DHW}. In August, similarly to the case of Berlin, heat at higher temperatures is used for TEGs to exploit renewable heat for the heat pump.

5.3. Energy flow analysis

The results of the analysis are presented, in form of Sankey diagrams, in Fig. 11-Fig. 16, where all the input and output flows are reported. All the quantities are in kWh/(m^2 year). Six scenarios were chosen for the analysis, i.e. SBs with 100% rooftop surface with solar collectors and NRBs with 50% rooftop surface with solar collectors, in the three examined cities (Madrid, Berlin and Helsinki). All the flows are in kWh/(m^{2}year).

A critical discussion of the results here presented will be done in the next section, whereas in the present only the main findings will be highlighted.

For the case of SBs-100% in Madrid (Fig. 11), it is possible to notice a different distribution of energy flows between the SBs and NRBs, which is essentially due to the different insulation, and therefore heating and cooling demand in the two cases. In particular, for SBs, the biggest part of solar energy is used for driving the cascade chiller in summer and for ORC and DHW in intermediate seasons. Only a small portion of heat is used for direct spaced

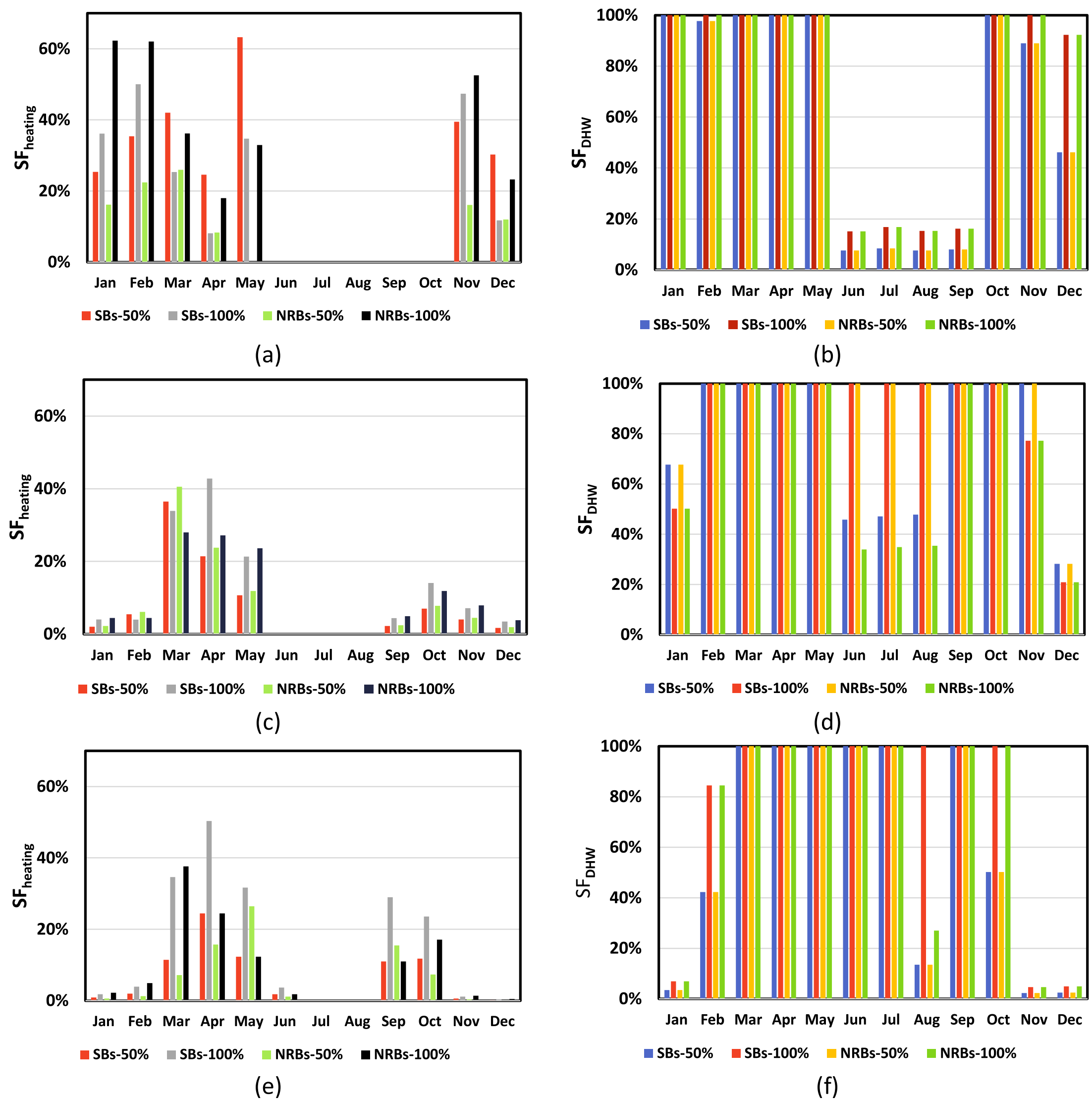

Fig. 10. Solar fraction for heating in (a) Madrid, (c) Berlin, (e) Helsinki and for DHW in (b) Madrid, (d) Berlin, (f) Helsinki.

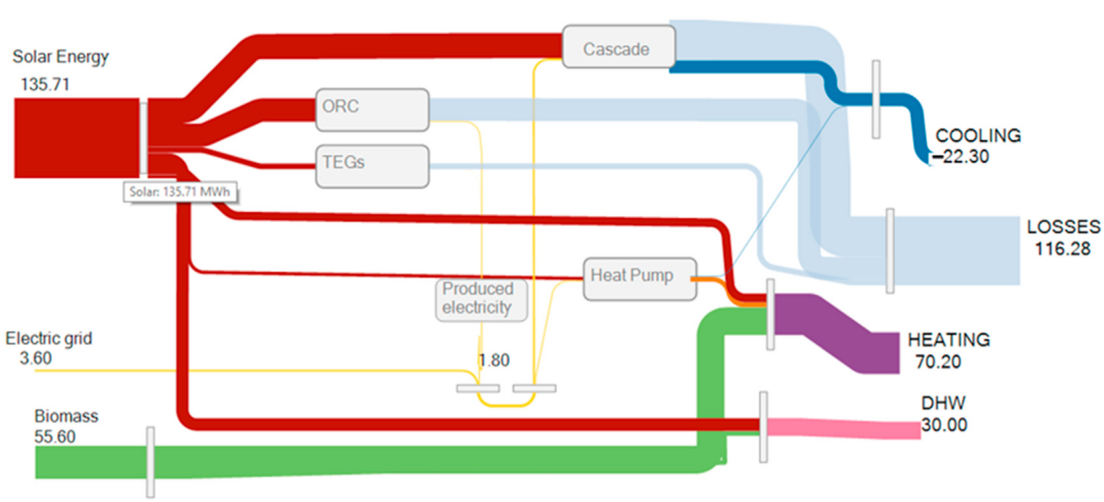

Fig. 11. Sankey diagram for SBs in Madrid with 100% solar collectors' surface. All the flows are in kWh/(m^{2}year).

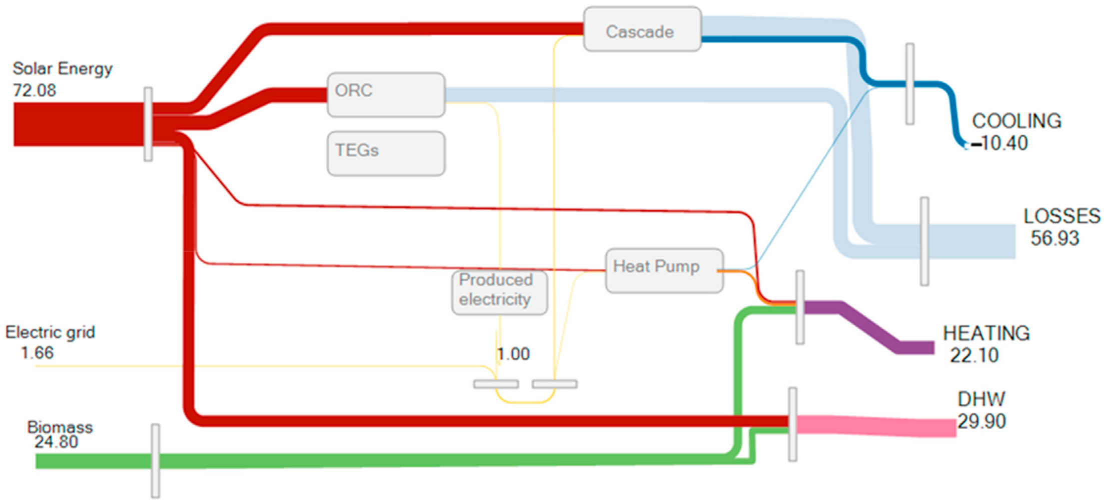

Fig. 12. Sankey diagram for NRBs in Madrid with 50% solar collectors' surface, values are in kWh/(m^{2}year).

heating and as evaporation heat source for the heat pump in winter. The contribution of biomass for direct space heating is relevant, whereas, as already stated before, the one for DHW is limited, thanks to the high SF_{DHW}. With the configuration presented, about 1/3 of overall electricity needed for auxiliaries can be self-produced. For the case of NRBs-50% (Fig. 12), the total annual distribution of solar contributions to cascade, ORC and DHW is almost equal. Compared to the previous case, heating and cooling demand is much lower and therefore the energy that the biomass boiler has to supply is about 45% of the SBs-100% case. In this situation, about half of electricity needed can be self-produced. For both SBs and NRBs, almost all cooling load is satisfied using the cascade chiller configuration, thanks to the high amount of solar heat at 90 °C that can be collected during summer. This allows at least 40% of reduction of electricity needs [24]. The heat losses to the ambient are mainly due to the condensation and adsorption heat dissipated in summer and by ORC and TEGs. Such a contribution of heat losses is obviously higher in SBs (116 kWh/(m^{2}year) vs. 57 kWh/(m^{2}year)) due to the higher utilization rate of these solar conversion systems.

For the case of Berlin for SBs-100%, what is interesting, and will be better discussed in section 6.1, is the different share of utilization of solar energy. Indeed, as shown in Fig. 13, about 30% of the overall solar energy in SBs is used for direct space heating and about 40% for driving the ORC. The remaining contributions of solar energy are almost equally divided between DHW, and the winter operation of the reversible heat pump (i.e. with solar collectors supplying the evaporation heat for the reversible heat pump). Fig. 13 shows that the biomass boiler supplies only a small fraction of the overall demand of DHW, but it is the main energy source for space heating. The reversible heat pump utilization for heating with high efficiency is exploited as well. The losses to the ambient mainly derive from the operation of ORC and, secondarily, from the TEGs and the reversible heat pump due to the condensation heat rejected during summer operation. Compared to the case of Madrid, it is possible to notice that solar energy harvested is about 43% lower, due to the higher latitude and low solar irradiation, but also heat losses to the ambient are lower, indicating that a smaller heat rejection system could be installed. As already noted in the previous section, the situation for NRBs-50% (Fig. 14) is similar, due to the similar construction materials of the buildings. Compared to the case of Madrid (NRBs-50% in Fig. 12), the amount of energy that the biomass boiler has to supply is about four times higher. At the same time, about twice the electricity is needed over the year, mainly due to the use of the heat pump for cooling in a stand-alone configuration.

The solar heat harnessed in Helsinki both for SBs-100% (Fig. 15) and NRBs-50% (Fig. 16) is similar to the one in Berlin (about 85 kWh/(m^{2}year) for SBs-100% and 68 kWh/(m^{2}year) for NRBs-50%). However, as it is reported in Table 3, this is obtained by using a wider extension of solar collectors, due to the different ratio between rooftop and conditioned area of the building. The contributions of the various heat sources are similar for the two cases, due to the small differences in the building constructive features. It is worth remarking that the contribution of the solar-assisted operation of the heat pump in winter is higher for the SBs-100% (due to the wider extension of the solar field), whereas for NRBs a higher integration from the biomass (130 kWh/(m^{2}year) against 100 kWh/(m^{2}year)) is needed. In SBs the TEGs can be better exploited, whereas in NRBs, both ORC and TEGs can be used. Cooling demand is negligible in both SBs and NRBs. It is worth noticing that the advantage in the choice of solar-thermal-based electricity production systems over PV, despite the lower efficiency, is justifiable from what was shown in this section. Indeed, the utilization of a thermal system with a proper control allows for the maximum exploitation of heat at different temperatures, which is not the case of a PV-based system that allows only electricity production and requires the operation of the solar panels at low temperatures.

6. Discussion of results

6.1. Evaluation of the best configuration for each climate zone

The proper selection of the optimal configuration for each climate zone should take into account energy, economic and technical considerations and come from a compromise among them. However, the aim of the present analysis is to maximise the share of renewables in each climate, thus selecting the renewable energy contributions as the key driver for the final choice. The effect of the different solar extensions and climates on the amount of heating and DHW demand was already presented in the previous section, but to better evaluate the obtained results, Fig. 17 shows the relative contributions of the different energy sources for covering the overall heating demand on monthly basis. In addition, in Fig. 18, the distribution of the heat sources for electricity is shown, for the same cases as in the analysis of the previous section

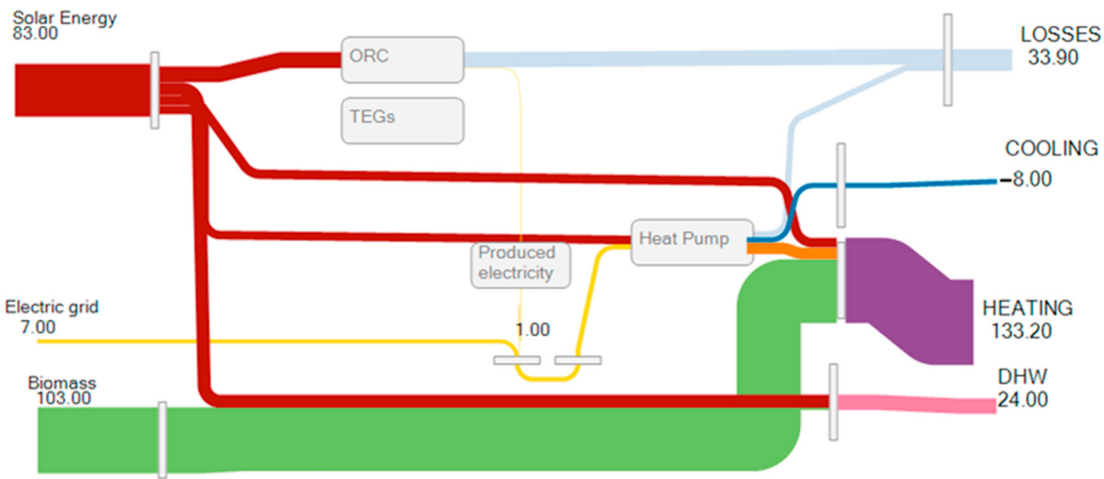

Fig. 13. Sankey diagram for SBs in Berlin with 100% solar collectors' surface. All the flows are in kWh/(m^{2}year).

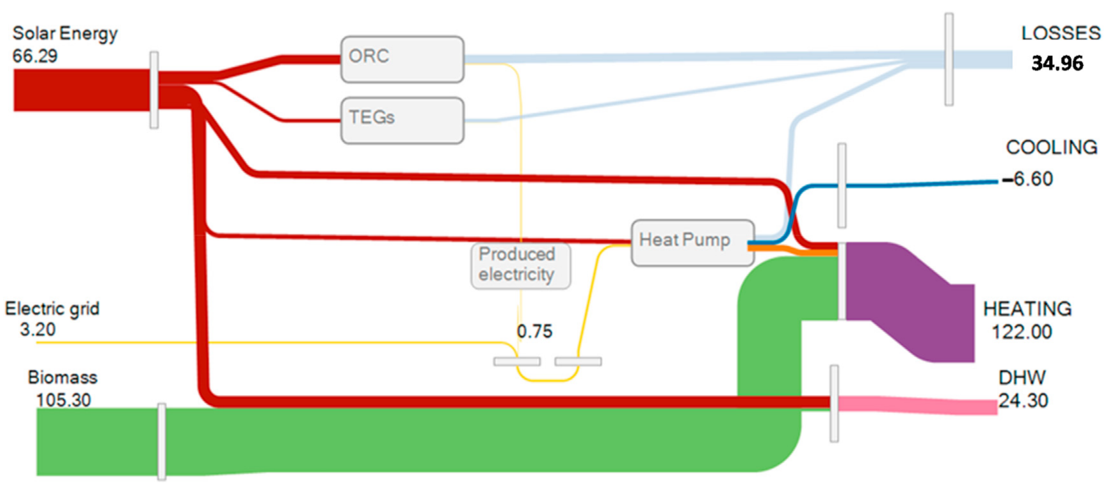

Fig. 14. Sankey diagram for NRBs in Berlin with 50% solar collectors' surface. All the flows are in kWh/(m^{2}year).

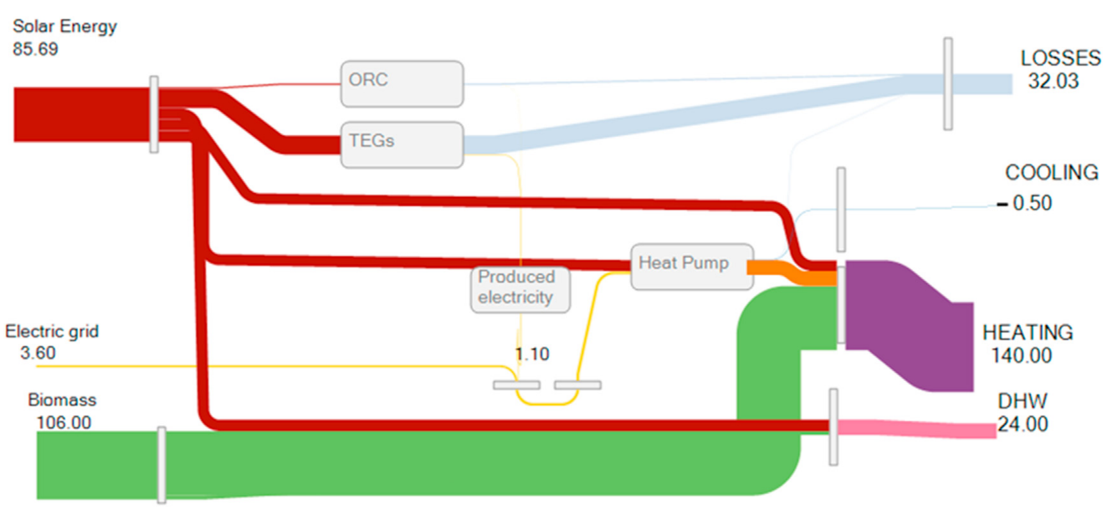

Fig. 15. Sankey diagram for SBs in Helsinki with 100% solar collectors' surface. All the flows are in kWh/(m^{2}year).

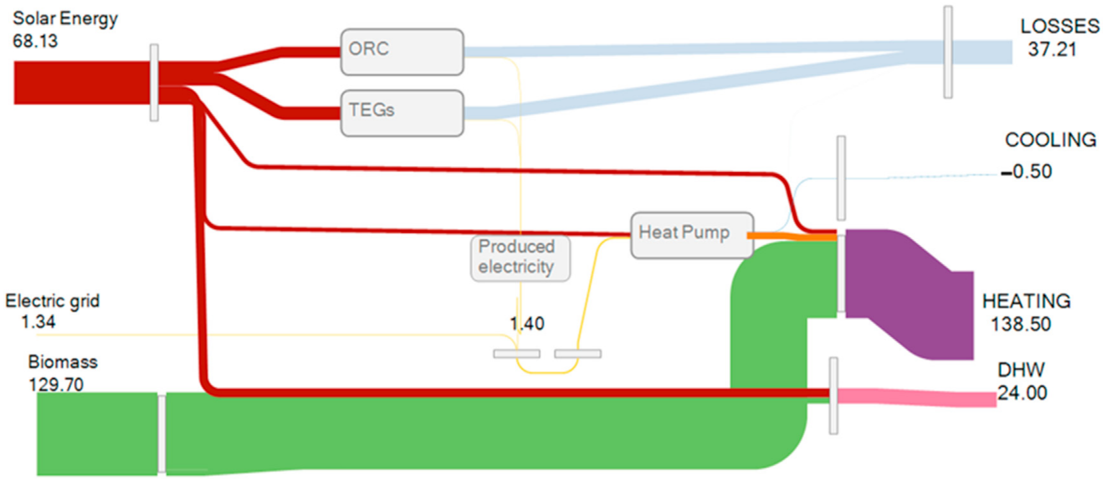

Fig. 16. Sankey diagram for NRBs in Helsinki with 50% solar collectors' surface. All the flows are in kWh/(m^{2}year).

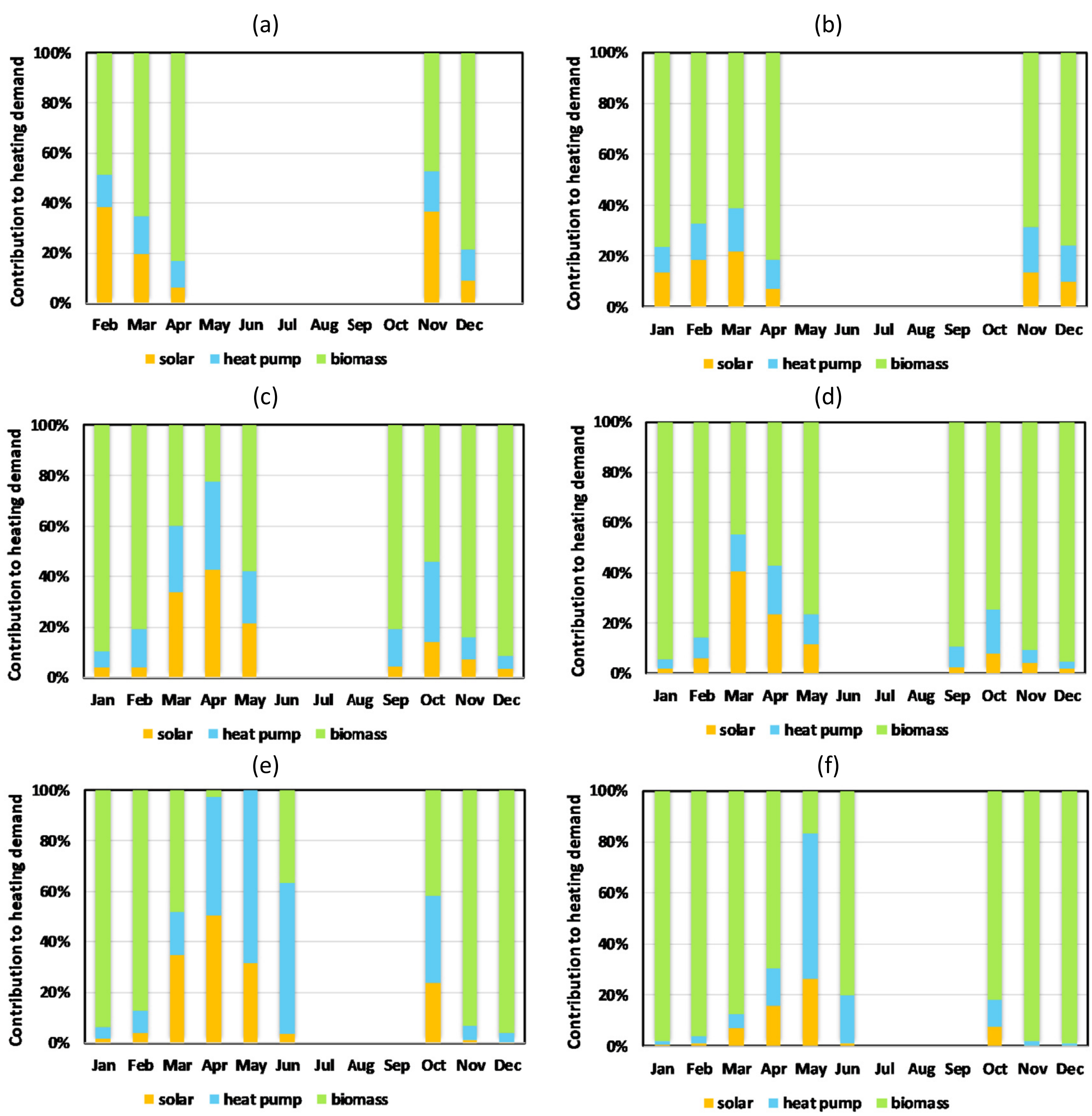

Fig. 17. Distribution of heating contributions from solar, biomass boiler and heat pump for covering heating demand for (a) SBs-100% in Madrid, (b) NRBs-50% in Madrid, (c) SBs-100% in Berlin, (d) NRBs-50% in Berlin, (e) SBs-100% in Helsinki, (f) NRBs-50% in Helsinki.

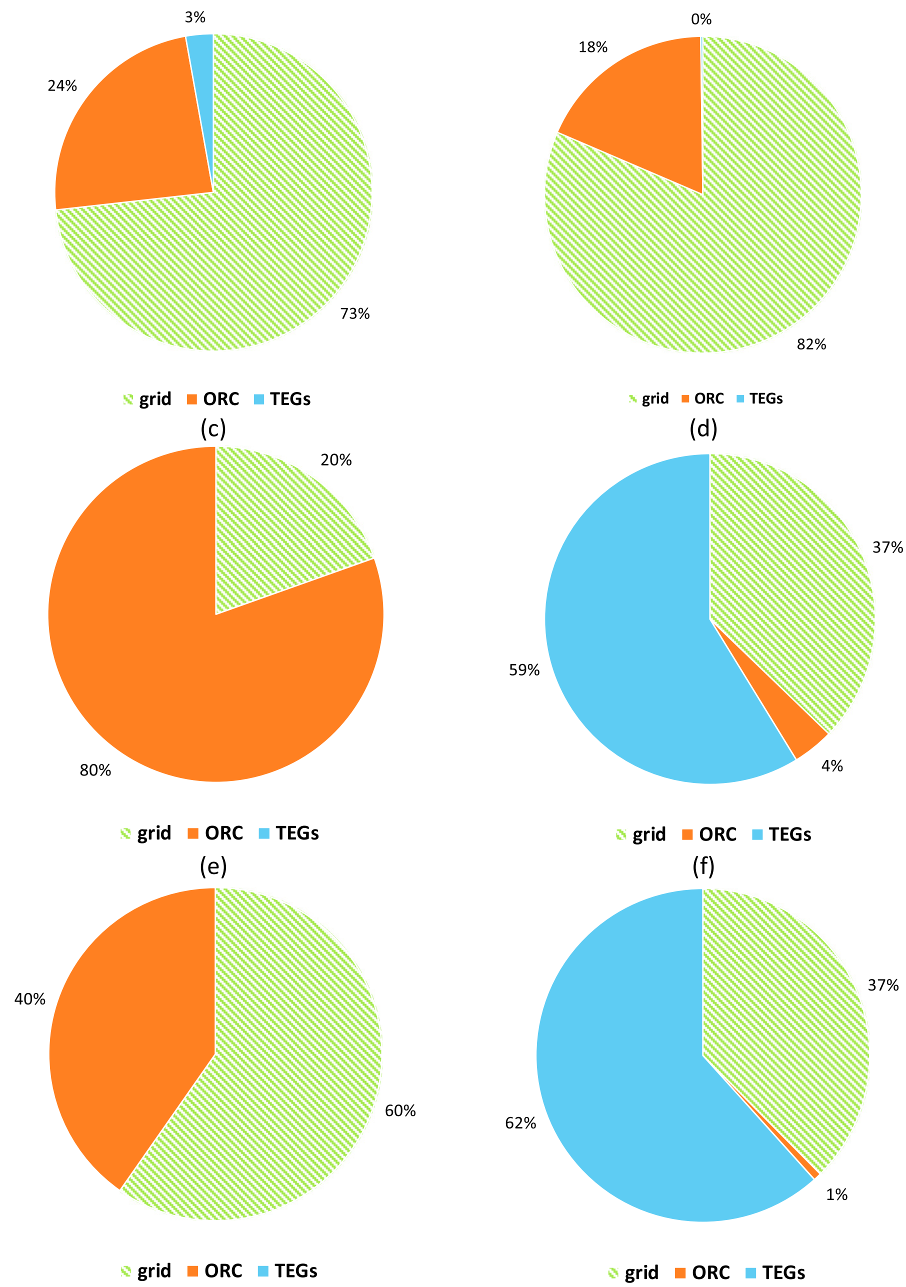

Fig. 18. Energy sources utilizations for electricity in Madrid for (a) SBs-100%, (b) NRBs-50%, in Berlin for (c) SBs-100% and (d) NRBs-50%, in Helsinki for (e) SBs-100% and (f) NRBs-50.

(SBs-100% and NRBs-50%). It is worth noticing that, despite the cost not being a leading criterion in the foreseen optimization of SolBio-Rev system, in the following analysis the possible simplifications of the systems in terms of layouts and solar collectors' area is discussed, that would also lead to a reduction of costs and system complexity.

In the previous section, for each climate, the cases of 100% solar collectors in SBs are compared with the case of 50% solar collectors in NRBs. Indeed, such a choice was made because in NRBs, which have better insulation, there is no need to increase the surface of solar collectors to cover, through renewables, a wide share of the energy demand of the building. On the contrary, for SBs, using 50% of rooftop only strongly penalises the share of renewables. In Madrid, only 40% of overall heating demand and cooling could be covered through renewables. In Berlin and Helsinki, only 25% of overall heating demand and 60% of DHW demand could be provided, whereas the effect on cooling demand would be negligible since it is already supplied from the reversible heat pump.

6.1.1. Madrid

In Madrid, the effect of solar collectors' surface extension is clear in how much heat can be exploited for space heating: doubling the collectors' surface allows to almost double the solar heat that can be directly used for space heating. The heat pump (in solar-assisted operation), supplies about 15% of heating demand for each month in both cases. It was already shown in Fig. 10 that even with 50% of solar collectors it was possible to get up to 100% DHW demand only using solar heat. The distribution of sources for heat generation is instead shown in Fig. 18a and b, where it is possible to show that TEGs are practically not used, whereas ORC can supply up to 24% of electricity needed. This is partly due to the necessity of using the high temperature heat to drive the cascade chiller during summer. However, the actual operation of the system could be improved by proper control. For instance, TEGs could be operated in "night-mode", i.e. exploiting at night the heat rejected at low temperatures and heat from the short-term storage (at T < 60 °C) for electricity production [23]. Considering that they have no moving parts, silent operation is possible, thus avoiding possible acoustic comfort problems for the occupants. Therefore, it is possible to state that the optimal configuration of Madrid can be obtained by a techno-economic analysis to define the optimal sizing of the solar collectors according to the amount of heating load with solar energy desired, since also with only 50% of solar collectors, more than 90% of cooling and DHW demand can be supplied directly using solar heat.

6.1.2. Berlin

In Berlin, increasing the surface of solar collectors leads to an increased amount of heat useful for DHW and as heat source for evaporation of the heat pump in winter, that can supply even up to 30% of heating demand during intermediate seasons (Fig. 17). Another marked difference shown in Fig. 18 is the different distribution of electricity provision in the two cases: for SBs-100%, the higher solar extension allows to reach higher temperatures for driving the ORC, whereas for NRBs-50%, TEGs are mostly exploited, due to the possible utilization of heat at lower temperatures. Compared to Madrid, however, in both cases examined, the integration needed from the grid is lower. These results show that, even in Northern climates, the potential for solar collectors' exploitation is high. At the same time, it is possible to notice from Fig. 18, that both in SBs and NRBs, the contemporary installation of TEGs and ORC does not actually result in an effectively higher production of electricity since there is a predominant contribution (TEGs in NRBs and ORC in SBs). In this case, then, a rationalisation of the configuration can then result in the selection of the best electricity generation device according to the specific features of the buildings and the extension of the solar collectors: in buildings with lower heating demand or when a higher number of solar collectors can be installed, ORC is preferable, otherwise it is advisable to make use of a standard heat pump (that presents less complexity and expenses) and optimise electricity generation through TEGs, thus decreasing also the cost of the solution.

6.1.3. Helsinki

For the case of Helsinki, it is possible to notice from Fig. 10 that the relative share of solar heat for DHW is still high, despite the northern location. Fig. 18 shows that, compared to the warmer climates where the ORC operation is not possible in summer due to the need for cooling with the cascade chiller, the share of renewable electricity is significantly higher, up to 62%. In this climate, where the biomass boiler would however run for longer hours, it could also be possible to exploit it for hybrid operation with the ORC to further increase the share of renewable electricity. In this case, it would be possible to prefer the installation of ORC instead of TEGs. It is also worth noticing, from the Sankey diagrams in Figs. 15 and 16, that, in Helsinki, the cooling demand is extremely low, i.e. 0.5 kWh/(m^2 year). At the same time, in Finland, electricity is produced with a high share of renewables [44–46], thus making the use of this source an interesting alternative when prioritising the different generation sources. This means that a higher share of heating load (especially in intermediate seasons) could be covered using the heat pump rather than the biomass boiler. An optimal configuration could then be represented by the SolBio-Rev system presented in Fig. 1 without TEGs but using a ground-source heat pump, to be exploited for cooling purposes in the summer and as heat source for evaporation of the reversible heat pump in winter, thus extending the operating hours of such a unit.

6.2. The role of nZEBs

Among the building typologies selected, the category of NRBs was specifically chosen since, for a vast extent, it includes buildings that are already compliant with nZEBs EU regulations to which all new buildings in the EU should comply by 2021. It was demonstrated, in the previous sections, that the construction features of the buildings strongly affect the utilization of energy resources. This is a result of the uttermost importance, since the relative weight of the contribution for DHW, compared to heating demand, is higher for nZEBs in general and the possibility of efficiently covering it from RES indicates the potentiality of the solution here proposed especially for this type of buildings. From the results in Fig. 17 it can also be noticed that the relative percentage of heating demand covered by the different technologies, are similar for SBs and NRBs in each climate, but with half of the solar collectors installed for NRBs. Therefore, considering that the building stock of the EU will evolve towards a higher number of nZEBs, and considering that this building typology allows an effective utilization of the solar-biomass generation system here presented, it is possible to state that the proposed solution has the potential for the application in the future energy system of the EU.

6.3. Comparison with other systems

A direct comparison of the solar-biomass system here presented with other solutions is difficult, since a homogeneous evaluation of boundary conditions should be applied. Nonetheless, a qualitative evaluation of the different systems proposed can be useful to highlight the main features of the different heat sources and technologies.

For instance, in Ref. [14], a micro-CHP system to cover electricity and heating demand of a single-family house is presented. What is clearly evidenced is that the optimal sizing of the system allows covering the warm season heat and electricity demand, which changes according to the different European climates. However, an auxiliary boiler is needed to integrate the winter demand. According to the climate, the optimal size of the auxiliary boiler is in the range 100–200% of the thermal capacity of the micro-CHP. The system is mostly penalized in warm countries, where the heat rejected to the ambient during summer is higher. One of the main features of the solar-biomass system is instead the possibility of using excess heat to produce electricity from TEGs and to drive the sorption chiller during summer, thus increasing the overall application scenarios in different geographical installations.

Another technology that is gaining interest in the last years, due to the transition towards an electrified energy system, is solar-assisted heat pump technology. Its application in households is discussed for instance in Refs. [18]. The solution proposed consists of a radiant floor heating system, a gas boiler and a photovoltaic-assisted air-source heat pump as heat sources, with a water tank as thermal energy storage. The study assessed the promising features of the system as a way to increase self-consumption of renewable-based energy by 30% compared to state-of-the-art systems, but still winter operation mainly relies on the gas boiler. Another difficulty encountered is the non-optimal operation of the heat pump under variable set-points, which should instead be used to exploit the storage tank as a means to accumulate energy produced when it is cheaper or when there is a maximum of renewable energy available. The use of a reversible heat pump allows covering both heating and cooling demand with a simple configuration, which reduces the complexity of a great amount compared to the

SolBio-Rev system. However, the results show that the operation of such a system with high efficiency still requires some efforts in the control and in the proper selection of components.

A more complex solar-driven system is presented in Ref. [21], which includes parabolic trough solar collectors and an organic Rankine cycle for combined cooling, heating and power (CCHP) is presented. In this system, a portion of the waste heat is used for heating through a heat exchanger and the other portion is used for cooling through a single-effect absorption chiller. In order to achieve good efficiencies, a balance based on demand variation on daily basis should be done, since increasing the stored thermal energy reduces the electrical efficiency and vice versa. The maximum electrical efficiency for the solar mode found was 15%, for the solar and storage mode was 7%. Only when cooling is needed, overall energy efficiencies (=energy used/overall solar energy) higher than 90% can be achieved, making the system more promising for the locations when substantial amount of cooling is needed. The SolBio-Rev system, instead, showed that a high utilization of renewable heat can be achieved also during winter season and also at higher latitudes.

In [22], a residential combined cooling heating and power (CCHP) system based on proton exchange membrane fuel cell (PEMFC) and solar energy is proposed. This system mainly consists of a PEMFC subsystem, an organic Rankine cycle/domestic hot water subsystem and a vapour compression cycle subsystem. Since the main source for the system is solar, the efficiency of the system is highly dependent on solar availability. One of the peculiar features of this system, which makes it close to the one here investigated, is its high flexibility: it is reduced to a CCH system driven by an ORC/DHW subsystem and a VCC subsystem when the current density is zero, and reduced to a CHP system with a PEMFC subsystem and a DHW subsystem when the solar radiation intensity is close to zero.

One remark worth considering is the difficulty in installing and operating hybrid systems, such as the one investigated in this paper and the ones reported in the literature in new and existing buildings. Indeed, the key aspect of SolBio-Rev system is the integration, as much as possible, of the different components, such as the TEGs with the solar collectors, that will be organised in form of a TEG block, and the sorption module and heat pump/ORC that will be realised as a single unit. It is also important to notice that current regulations in several EU countries already require the installation of renewable-driven equipment to cover, through renewables a share of the building energy demand [41] and therefore the added complication due to the various components of the system leverages on existing practices and knowledge from designers and installers and can be compensated through proper training actions.

6.4. Is there a 100% renewable scenario?

As previously shown, the potentiality of the solar-biomass system presented is high. However, still large losses are present, which are mainly due to the utilization of TEGs and ORC. Indeed, further improvement in the performance of the system could be achieved by using the waste heat from these components. Indeed, in the literature, the possibility of using the waste heat from ORC was investigated either for direct space heating applications [47] or for improving the efficiency of a heat pump [48]. Similarly, the heat from TEGs could be recovered through a ventilation system to improve the energy efficiency of green buildings, as suggested in Ref. [49], while improving the performance of the TEG itself. Moreover, if a penalisation in terms of overall COP is accepted, the use of low-temperature waste heat from TEGs (50–60 °C) could also be used in intermediate seasons for DHW or to drive the sorption chiller [50].

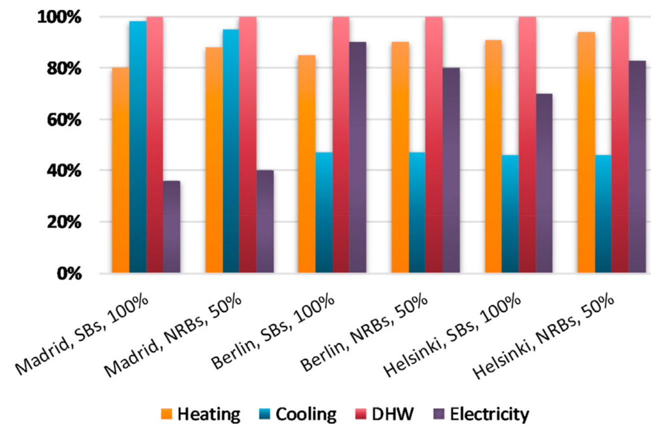

Fig. 19. Overall share of renewables.

Finally, the results were critically analysed with the aim of defining the potentiality of SolBio-Rev system here presented to reach 100% renewable for residential applications. To this aim, the contributions to the overall heating, cooling, DHW and electricity demand were aggregated according to renewable (solar and biomass) and non-renewable ones.

To take into account that part of the electricity absorbed from the grid comes from renewable generation, the contribution of the electricity was weighted considering the following share of renewable generation for the national electrical grid: 47% in Germany [51], 46% in Finland [52], and 33% in Spain [53].

The results in Fig. 19 show that without any specific control strategy or optimized control, it is already possible to obtain 100% cooling (in Madrid) and DHW from RES (in all climates), and more than 80% of heating from RES (with the only exception of Madrid in SBs, that is at 80%). In section 6.1, the possible strategies to improve electricity generation from RES were discussed as well, indicating a path towards a substantial increase also of this contribution. In addition, the application of suitable control models, that will be applied in the next stages of the development of the present project, can increase the penetration of renewables by 25% [10], thus further stressing that the target of a 100% RES based system is within the reach for the multi-generation system here presented.

7. Conclusions and future research perspectives

In this paper a renewable-driven energy system suitable for residential buildings was analysed in different locations, with the aim of assessing its potentiality for a massive decarbonization of the actual and future building stock. The main components of the hybrid system are: solar thermal collectors with thermoelectric generators; a sorption module; a reversible heat pump/ORC and a biomass boiler, arranged in a flexible configuration. The system was designed in order to cover heating, cooling and DHW demand with a high share of renewables according to the specificity of the installation (i.e. the location and the electric/thermal energy ratio of the building). The application of the system in Madrid, Berlin and Helsinki for multi-family houses and two main building typologies, i.e., standard (non-renovated) new and renovated residential buildings was evaluated through an energy flow analysis, considering also the possibility of installing different solar collectors' surfaces. Main goal of the analysis was to show the share of renewables achievable in the different latitudes, highlighting the relative contribution of the different heat sources and their different utilization according to building-specific and climate-related issues. The main outcomes of the energy analysis are the possibility of achieving solar fractions for DHW extremely high (i.e. >80%) even in northern climates and the possibility of covering a wide share of heating demand (up to 60% in Madrid and up to 30% in Berlin and Helsinki) thanks to solar heat only during intermediate seasons. In Madrid, the exploitation of solar heat as driving source for a combined sorption-compression cycle in summer allows an efficient cooling, with significant savings in terms of electricity needed.

In addition, it was shown that the proposed configuration is widely adaptable to different situations without penalising the overall share of renewables. For instance, it was demonstrated that if there is the need to reduce the size of the solar field, it is still possible to cover a significant part of DHW demand and electricity demand, by preferring TEGs over the ORC.

Finally, analysing the results for nZEBs the potentialities of the system were further assessed, proving that the solution proposed has the potentiality to reach the 100% renewable energy target in the future EU building stock.

Starting from these results, the future directions of research for the full exploitation of renewable energy in buildings can be identified: a key issue is the need for optimized control strategies, able to predict and drive the operation of complex systems, based on building load, user demand and climate conditions. Another driver for future research in this field is the development of proper sizing methodologies and tools that consider the system from a holistic point of view. Indeed, in the present analysis, the final goal was to demonstrate the paths to be followed to maximise renewable energy generation for buildings self-consumption in a kind of system never presented before. However, as technology matures and its readiness level and marketability increase, techno-economic evaluations cannot be disregarded and therefore suitable tools should be developed to cope with them. Finally, technological development of the various heat sources and uses, in the view of inter-operable and easy-to-install solutions will remove acceptance barriers for these systems, really creating an increased market and strengthening the role of renewables.

CRediT authorship contribution statement

Valeria Palomba: Writing - original draft, Visualization, Formal analysis, Validation, Methodology. **Emiliano Borri:** Writing - original draft, Visualization, Formal analysis, Validation, Methodology. **Antonios Charalampidis:** Writing - review & editing, Formal analysis, Validation, Methodology. **Andrea Frazzica:** Writing - review & editing, Conceptualization. **Luisa F. Cabeza:** Writing - review & editing, Conceptualization. **Sotirios Karellas:** Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] L. Belussi, B. Barozzi, A. Bellazzi, L. Danza, A. Devitofrancesco, C. Fanciulli, M. Ghellere, G. Guazzi, I. Meroni, F. Salamone, F. Scamoni, C. Scrosati, A review of performance of zero energy buildings and energy efficiency solutions, J. Build. Eng. 25 (2019), 100772, https://doi.org/10.1016/J.JOBE.2019.100772.

[2] European Commission, Energy performance of buildings directive (2018/844/EU) (n.d.), https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings/energy-performance-buildings-directive. (Accessed 1 November 2019).

[3] European Commission, Energy efficiency directive 2012/27/EU (n.d.), https://ec.europa.eu/energy/en/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive. (Accessed 1 November 2019).

[4] A. Thonipara, P. Runst, C. Ochsner, K. Bizer, Energy efficiency of residential buildings in the European Union – an exploratory analysis of cross-country consumption patterns, Energy Pol. 129 (2019) 1156–1167, https://doi.org/10.1016/J.ENPOL.2019.03.003.

[5] D. D'Agostino, D. Parker, P. Melià, Environmental and economic implications of energy efficiency in new residential buildings: a multi-criteria selection approach, Energy Strateg. Rev. 26 (2019), 100412, https://doi.org/10.1016/J.ESR.2019.100412.

[6] S.B. Sadineni, S. Madala, R.F. Boehm, Passive building energy savings: a review of building envelope components, Renew. Sustain. Energy Rev. 15 (2011) 3617–3631, https://doi.org/10.1016/J.RSER.2011.07.014.

[7] A. Tejero-González, M. Andrés-Chicote, P. García-Ibáñez, E. Velasco-Gómez, F.J. Rey-Martínez, Assessing the applicability of passive cooling and heating techniques through climate factors: an overview, Renew. Sustain. Energy Rev. 65 (2016) 727–742, https://doi.org/10.1016/J.RSER.2016.06.077.

[8] V. Vakiloroaya, B. Samali, A. Fakhar, K. Pishghadam, A review of different strategies for HVAC energy saving, Energy Convers. Manag. 77 (2014) 738–754, https://doi.org/10.1016/J.ENCONMAN.2013.10.023.

[9] E. Fabrizio, F. Seguro, M. Filippi, Integrated HVAC and DHW production systems for zero energy buildings, Renew. Sustain. Energy Rev. 40 (2014) 515–541, https://doi.org/10.1016/J.RSER.2014.07.193.

[10] N. Aste, M. Manfren, G. Marenzi, Building Automation and Control Systems and performance optimization: a framework for analysis, Renew. Sustain. Energy Rev. 75 (2017) 313–330, https://doi.org/10.1016/J.RSER.2016.10.072.

[11] W. Zappa, M. Junginger, M. van den Broek, Is a 100% renewable European power system feasible by 2050? Appl. Energy 233–234 (2019) 1027–1050, https://doi.org/10.1016/J.APENERGY.2018.08.109.

[12] H.R. Ellamla, I. Staffell, P. Bujlo, B.G. Pollet, S. Pasupathi, Current status of fuel cell based combined heat and power systems for residential sector, J. Power Sources 293 (2015) 312–328, https://doi.org/10.1016/J.JPOWSOUR.2015.05.050.

[13] V. Palomba, M. Ferraro, A. Frazzica, S. Vasta, F. Sergi, V. Antonucci, Experimental and numerical analysis of a SOFC-CHP system with adsorption and hybrid chillers for telecommunication applications, Appl. Energy 216 (2018) 620–633, https://doi.org/10.1016/j.apenergy.2018.02.063.

[14] V. Liso, Y. Zhao, N. Brandon, M.P. Nielsen, S.K. Kær, Analysis of the impact of heat-to-power ratio for a SOFC-based mCHP system for residential application under different climate regions in Europe, Int. J. Hydrogen Energy 36 (2011) 13715–13726, https://doi.org/10.1016/J.IJHYDENE.2011.07.086.

[15] P. Nema, R.K. Nema, S. Rangnekar, A current and future state of art development of hybrid energy system using wind and PV-solar: a review, Renew. Sustain. Energy Rev. 13 (2009) 2096–2103, https://doi.org/10.1016/J.RSER.2008.10.006.

[16] A.C. Duman, Ö. Güler, Techno-economic analysis of off-grid PV/wind/fuel cell hybrid system combinations with a comparison of regularly and seasonally occupied households, Sustain. Cities Soc 42 (2018) 107–126, https://doi.org/10.1016/J.SCS.2018.06.029.

[17] C. Camarasa, C. Nägeli, Y. Ostermeyer, M. Klippel, S. Botzler, Diffusion of energy efficiency technologies in European residential buildings: a bibliometric analysis, Energy Build. 202 (2019), 109339, https://doi.org/10.1016/J.ENBUILD.2019.109339.

[18] E. Zanetti, M. Aprile, D. Kum, R. Scoccia, M. Motta, Energy saving potentials of a photovoltaic assisted heat pump for hybrid building heating system via optimal control, J. Build. Eng. 27 (2020), 100854, https://doi.org/10.1016/J.JOBE.2019.100854.

[19] M.A. Obalanlege, Y. Mahmoudi, R. Douglas, E. Ebrahimnia-Bajestan, J. Davidson, D. Bailie, Performance assessment of a hybrid photovoltaic-thermal and heat pump system for solar heating and electricity, Renew. Energy (2019), https://doi.org/10.1016/J.RENENE.2019.10.061.

[20] H. Chang, Y. Liu, J. Shen, C. Xiang, S. He, Z. Wan, M. Jiang, C. Duan, S. Shu, Experimental study on comprehensive utilization of solar energy and energy balance in an integrated solar house, Energy Convers. Manag. 105 (2015) 967–976, https://doi.org/10.1016/J.ENCONMAN.2015.08.061.

[21] F.A. Al-Sulaiman, F. Hamdullahpur, I. Dincer, Performance assessment of a novel system using parabolic trough solar collectors for combined cooling,

heating, and power production, Renew. Energy 48 (2012) 161–172, https://doi.org/10.1016/J.RENENE.2012.04.034.
[22] H. Chang, Z. Wan, Y. Zheng, X. Chen, S. Shu, Z. Tu, S.H. Chan, Energy analysis of a hybrid PEMFC–solar energy residential micro-CCHP system combined with an organic Rankine cycle and vapor compression cycle, Energy Convers. Manag. 142 (2017) 374–384, https://doi.org/10.1016/J.ENCONMAN.2017.03.057.
[23] K. Karthick, S. Suresh, M.M.M.D. Hussain, H.M. Ali, C.S.S. Kumar, Evaluation of solar thermal system configurations for thermoelectric generator applications: a critical review, Sol. Energy 188 (2019) 111–142, https://doi.org/10.1016/J.SOLENER.2019.05.075.
[24] S. Vasta, V. Palomba, D. La Rosa, W. Mittelbach, Adsorption-compression cascade cycles: an experimental study, Energy Convers. Manag. 156 (2018) 365–375, https://doi.org/10.1016/j.enconman.2017.11.061.
[25] V. Palomba, G.E. Dino, A. Frazzica, Coupling sorption and compression chillers in hybrid cascade layout for efficient exploitation of renewables: sizing, design and optimization, Renew. Energy 154 (2020) 11–28, https://doi.org/10.1016/J.RENENE.2020.02.113.
[26] S. Staub, P. Bazan, K. Braimakis, D. Müller, C. Regensburger, D. Scharrer, B. Schmitt, D. Steger, R. German, S. Karellas, M. Pruckner, E. Schlücker, S. Will, J. Karl, Reversible heat pump–organic Rankine cycle systems for the storage of renewable electricity, Energies 11 (2018) 1352, https://doi.org/10.3390/en11061352.
[27] C. Mateu-Royo, A. Mota-Babiloni, J. Navarro-Esbrí, B. Peris, F. Molés, M. Amat-Albuixech, Multi-objective optimization of a novel reversible High-Temperature Heat Pump-Organic Rankine Cycle (HTHP-ORC) for industrial low-grade waste heat recovery, Energy Convers. Manag. 197 (2019), 111908, https://doi.org/10.1016/J.ENCONMAN.2019.111908.
[28] A. Faddouli, H. Labrim, S. Fadili, A. Habchi, B. Hartiti, M. Benaissa, M. Hajji, H. EZ-Zahraouy, E. Ntsoenzok, A. Benyoussef, Numerical analysis and performance investigation of new hybrid system integrating concentrated solar flat plate collector with a thermoelectric generator system, Renew. Energy 147 (2020) 2077–2090, https://doi.org/10.1016/J.RENENE.2019.09.130.
[29] S. Khanmohammadi, M.M. Baseri, P. Ahmadi, A.A.A.A. Al-Rashed, M. Afrand, Proposal of a novel integrated ocean thermal energy conversion system with flat plate solar collectors and thermoelectric generators: energy, exergy and environmental analyses, J. Clean. Prod. 256 (2020) 120600, https://doi.org/10.1016/J.JCLEPRO.2020.120600.
[30] A. Vallati, P. Ocłoń, C. Colucci, L. Mauri, R. de Lieto Vollaro, J. Taler, Energy analysis of a thermal system composed by a heat pump coupled with a PVT solar collector, Energy 174 (2019) 91–96, https://doi.org/10.1016/J.ENERGY.2019.02.152.
[31] B. Kılkış, Development of a composite PVT panel with PCM embodiment, TEG modules, flat-plate solar collector, and thermally pulsing heat pipes, Sol. Energy 200 (2020) 89–107, https://doi.org/10.1016/J.SOLENER.2019.10.075.
[32] R. Lazzarin, M. Noro, Photovoltaic/Thermal (PV/T)/ground dual source heat pump: optimum energy and economic sizing based on performance analysis, Energy Build. 211 (2020), 109800, https://doi.org/10.1016/J.ENBUILD.2020.109800.
[33] P. Zangheri, R. Armani, M. Pietrobon, L. Pagliano, M.F. Boneta, A. Müller, Heating and cooling energy demand and loads for building types in different countries of the EU, Polytech. Univ. Turin, End-Use Effic, Res. Gr. 3 (2014).
[34] E. Concerted Action, Implementing the Energy Performance of Buildings Directive (EPBD)–Featuring Country Reports, (2015), 2016.
[35] S. Longo, V. Palomba, M. Beccali, M. Cellura, S. Vasta, Energy balance and life cycle assessment of small size residential solar heating and cooling systems equipped with adsorption chillers, Sol. Energy 158 (2017) 543–558. http://www.sciencedirect.com/science/article/pii/S0038092X17308745. (Accessed 8 November 2017).
[36] J. Mascuch, V. Novotny, V. Vodicka, J. Spale, Z. Zeleny, Experimental development of a kilowatt-scale biomass fired micro – CHP unit based on ORC with rotary vane expander, Renew. Energy (2018), https://doi.org/10.1016/J.RENENE.2018.08.113.
[37] Y.J. Dai, H.M. Hu, T.S. Ge, R.Z. Wang, P. Kjellsen, Investigation on a mini-CPC hybrid solar thermoelectric generator unit, Renew. Energy 92 (2016) 83–94, https://doi.org/10.1016/J.RENENE.2016.01.060.
[38] T. Loga, B. Stein, N. Diefenbach, TABULA building typologies in 20 European countries—making energy-related features of residential building stocks comparable, Energy Build. 132 (2016) 4–12.
[39] J. Garcia, L. Kranzl, Ambition levels of nearly zero energy buildings (nZEB) definitions: an approach for cross-country comparison, Buildings 8 (2018) 143.
[40] C.T. de la Edificación, Documento básico HE Ahorro de energía, CTE, DB-HE, 2013.
[41] E. Action, Implementing the Energy Performance of Buildings Directive (EPBD), Featuring Country Reports, EU Publications Office, 2016.
[42] Affordable Zero Energy Buildings, Definition of Indicators and Assessment Methods for Cost Effective nZEB and Energy+ Buildings, 2019.
[43] S.A. Kalogirou, in: S.A.B.T.-S.E.E. Kalogirou (Ed.), Chapter Five - Solar Water Heating Systems, Academic Press, Boston, 2009, pp. 251–314, https://doi.org/10.1016/B978-0-12-374501-9.00005-4.
[44] A. Holma, P. Leskinen, T. Myllyviita, K. Manninen, L. Sokka, T. Sinkko, K. Pasanen, Environmental impacts and risks of the national renewable energy targets – a review and a qualitative case study from Finland, Renew. Sustain. Energy Rev. 82 (2018) 1433–1441, https://doi.org/10.1016/J.RSER.2017.05.146.
[45] P. Bórawski, A. Bełdycka-Bórawska, E.J. Szymańska, K.J. Jankowski, B. Dubis, J.W. Dunn, Development of renewable energy sources market and biofuels in the European Union, J. Clean. Prod. 228 (2019) 467–484, https://doi.org/10.1016/J.JCLEPRO.2019.04.242.
[46] M. Child, C. Breyer, The role of energy storage solutions in a 100% renewable Finnish energy system, Energy Procedia 99 (2016) 25–34, https://doi.org/10.1016/J.EGYPRO.2016.10.094.
[47] G. Carraro, V. Bori, A. Lazzaretto, G. Toniato, P. Danieli, Experimental investigation of an innovative biomass-fired micro-ORC system for cogeneration applications, Renew. Energy 161 (2020) 1226–1243, https://doi.org/10.1016/j.renene.2020.07.012.
[48] H. Yu, T. Gundersen, X. Feng, Process integration of organic Rankine cycle (ORC) and heat pump for low temperature waste heat recovery, Energy 160 (2018) 330–340, https://doi.org/10.1016/j.energy.2018.07.028.
[49] Y. Cai, W.W. Wang, C.W. Liu, W.T. Ding, D. Liu, F.Y. Zhao, Performance evaluation of a thermoelectric ventilation system driven by the concentrated photovoltaic thermoelectric generators for green building operations, Renew. Energy 147 (2020) 1565–1583, https://doi.org/10.1016/j.renene.2019.09.090.
[50] K. Braimakis, Solar ejector cooling systems: a review, Renew. Energy (2020), https://doi.org/10.1016/j.renene.2020.09.079.
[51] DESTATIS Statistiches Bundesamt, Stromerzeugung im 2. Quartal 2019. https://www.destatis.de/DE/Presse/Pressemitteilungen/2019/09/PD19_367_43312.html, 2019. (Accessed 1 December 2019).
[52] Statistics Finland, Energy, Production of electricity and heat. https://www.stat.fi/til/salatuo/index_en.html, 2019. (Accessed 1 December 2019).
[53] Red Eléctrica de España, National statistical series. https://www.ree.es/en/datos/publications/national-statistical-series, 2019. (Accessed 1 December 2019).

Further reading

[54] U. of W. Solar Energy Laboratory, TRNSYS 17 Documentation, (n.d).
[55] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, Wiley, 2013.
[56] C. Stanciu, D. Stanciu, Optimum tilt angle for flat plate collectors all over the World – a declination dependence formula and comparisons of three solar radiation models, Energy Convers. Manag. 81 (2014) 133–143, https://doi.org/10.1016/J.ENCONMAN.2014.02.016.
[57] VDI-wärmeatlas, Springer Berlin Heidelberg, Berlin, Heidelberg, 2002, https://doi.org/10.1007/978-3-662-10743-0.
[58] S. Vasta, V. Palomba, D. La Rosa, W. Mittelbach, Adsorption-compression cascade cycles: an experimental study, Energy Convers. Manag. 156 (2018) 365–375, https://doi.org/10.1016/j.enconman.2017.11.061.
[59] F. Mauthner, S. Fischer, Overheating prevention and stagnation handling in solar process heat applications. http://task49.iea-shc.org/Data/Sites/7/frank_iea_shc_task49_overheatingstagnationreport_approved_v-2-3.pdf, 2015.